

Mission to the Solar System: Exploration and Discovery

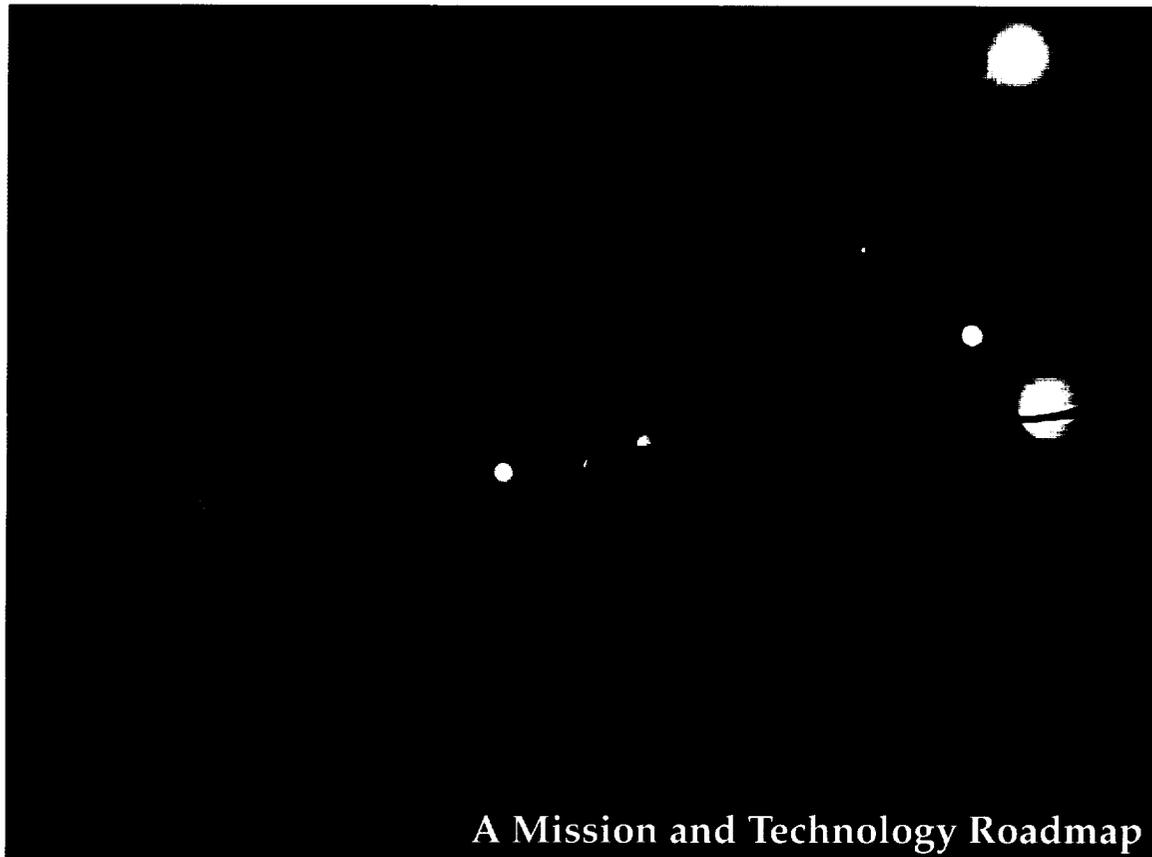
A Mission and Technology
Roadmap

JÜRGEN RAHE

1940-1997

We dedicate this work to the memory of Jürgen Rahe, scientist, educator, diplomat, initiator and motivator, and the very finest of administrators. From his Ph.D. thesis about comets under Karl Würm to the International Halley Watch Atlas of Large-Scale Phenomena (1992), he remained a scientist, always with a scientist's view of what was important. He taught as a professor at the University of Erlangen-Nürnberg. He served as director of the Dr. Remeis Observatory and its interactions with the city of Bamberg, as Eastern Hemisphere leader of the International Halley Watch, and as a senior NASA official interacting with other space agencies. In all his relationships as a sponsor of research by universities, laboratories, observatories, and individual scientists, he always remained the calm, even-tempered diplomat, achieving his goals by careful reasoning and explanation. His activities in initiating new goals and his motivating of those whose actions were needed to achieve both new and old goals were never blatant, but they can be seen in NASA participation in the Keck II upgraded observatory and in the very document to which these words are appended. He was an unparalleled administrator, who gave unstintingly of his time and effort to achieve the betterment of space science and the support of its practitioners. His loss in a freak accident, when a tree fell on his car, has been devastating to his multitude of friends, and its effects on space science will be felt for years to come. *Requiescat in pace*, Jürgen. Your good works will never be forgotten.

MISSION TO THE SOLAR SYSTEM: EXPLORATION AND DISCOVERY



The Roadmap Development Team

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PREFACE

Solar System exploration addresses some of humanity's most fundamental questions:

- How and when did life form on Earth?
- Does life exist elsewhere in the Solar System or in the Universe?
- How did the Solar System form and evolve in time?
- What can the other planets teach us about the Earth?

This document describes a Mission and Technology Roadmap, which addresses steps that can be taken to answer these and other fundamental questions about our Solar System.

The Mission and Technology Roadmap was developed in support of the Solar System Exploration theme in NASA's Office of Space Science. The intent of the Roadmap is to provide reference and background materials for NASA's Space Science Enterprise Strategic Plan (November 1997).

The document is based on deliberations and discussions by a Roadmap Development Team, NASA/JPL/Industry Participants Working Teams, and Industry Participants (Appendix A, Participants). The Roadmap Development Team was composed of scientists, engineers, educators, and technologists appointed by Dr. Wesley Huntress, Jr., NASA Associate Administrator for Space Science, and Dr. Jürgen Rahe, the Science Program Director for Solar System Exploration. Dr. Charles Elachi, Director for Space and Earth Science Programs Directorate, Jet Propulsion Laboratory led the Roadmap activity. Dr. Elachi formed two working teams, which each prepared Roadmap options. Suggestions were also solicited from the entire science community at a science workshop held at the California Institute of Technology on March 4–5, 1996. The various ideas and proposals were discussed by the Roadmap Development Team and combined into the Mission and Technology Roadmap outlined here.

The Vision of the Roadmap Development Team was to define the next evolutionary steps in *in situ* exploration, sample return, and completion of the overall Solar System survey that will lead to answers to fundamental questions about the Solar System. Guidelines from Huntress and Rahe were to "develop a visionary, but affordable, mission and technology development Roadmap for the exploration of the Solar System in the 2000 to 2012 timeframe." The Roadmap Development Team did not address supporting research and technology, ground-based observations, or laboratory research. These are critical components of the U.S. program, and their omission here should not be interpreted as meaning they are of less importance than flight missions.

This Mission to the Solar System Roadmap is one of four science and technology "Roadmaps" written to support NASA's Space Science Enterprise planning process. Roadmaps for each of the four "Themes" in the Office of Space Science (Astronomical Search for Origins, Structure and Evolution of the Universe, Sun-Earth Connection, and Solar System Exploration) were developed as part of the Enterprise planning process. The four Roadmaps, together with National Academy of Sciences reports, provide reference and background information for NASA's Space Science Enterprise Strategic Plan.

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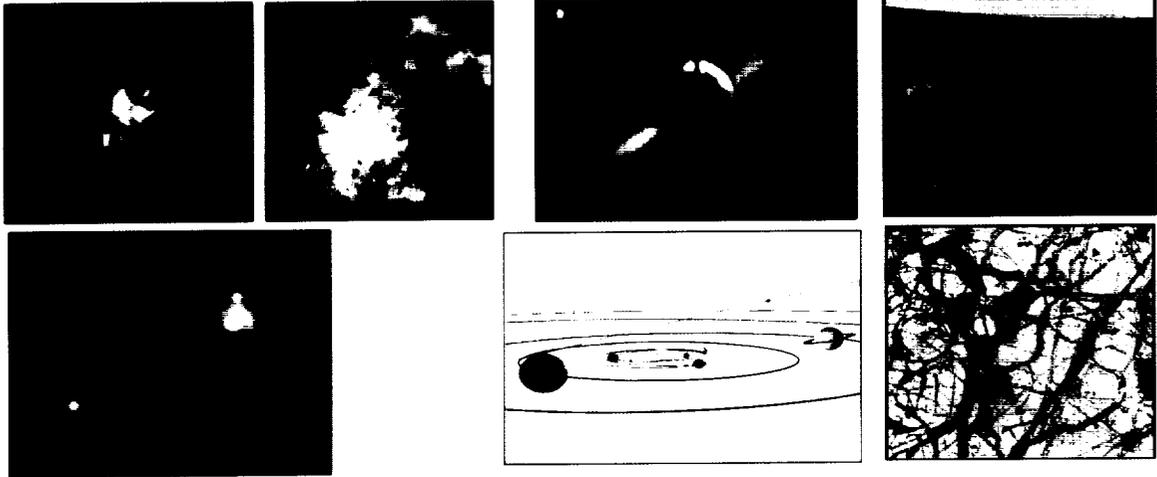
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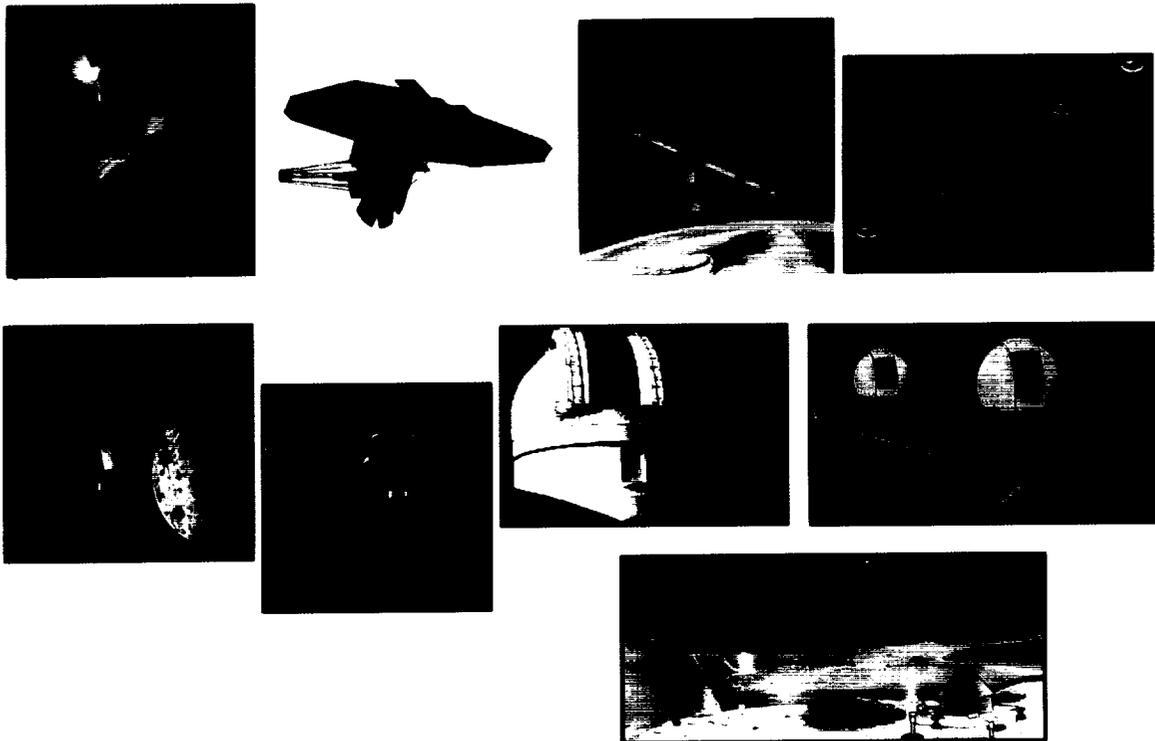
FROM CLOUDS TO STARS TO PLANETS ...TO LIFE?



How did galaxies, stars and planetary systems form?

Are there Earth-like planets around nearby stars?

Did life start elsewhere in the solar system?



CHAPTER 1

OVERVIEW

Solar System exploration using robotic and manned spacecraft has been ongoing for more than thirty-five years. From the first robotic spacecraft launched by the former U.S.S.R. to the Moon in January 1959, to the multitude of spacecraft that have visited every planet from Mercury to Neptune as well as satellites, asteroids, and comets, humanity has nearly completed its initial reconnaissance of the Solar System. These activities have benefitted all humanity by increasing our understanding of the Solar System, including Earth, and by raising new insights regarding the possibility that life could exist or has existed in the past on other planets and satellites in the Solar System. NASA has played a leading role in this exploration. An overview of NASA's Planetary Space Missions followed by a listing of U.S. Lunar and Planetary missions through 1997 is given in Appendix B. References to former U.S.S.R., European, and Japanese missions can also be found in Appendix B.

In the past few years, many new exciting discoveries about our Solar System have been made. We have studied meteorites from Mars, one of which (ALH84001) shows evidence of ancient water and the chemical building blocks of life. We have observed what may be ice floes above a liquid water ocean on Jupiter's moon Europa. We have landed a small roving vehicle on Mars, driven around, and taken photographs. In other scientific areas, equally exciting developments have also taken place. Stellar nurseries, where stars are born, have been observed. Planetary companions of nearby stars have apparently been detected through the small motions they produce in their primary stars. With these and many other scientific and technologic developments in recent years, 1997 was seen as the right time for a fresh evaluation of the direction of space science within NASA. The NASA Office of Space Science, under the leadership of the Associate Administrator for the Space Science Enterprise, began developing science and technology roadmaps for each of the four themes in the Office of Space Science (Astronomical Search for Origins, Structure and Evolution of the Universe, Sun-Earth Connection, Solar System Exploration). The Roadmap for Solar System Exploration is presented in this document.

The framework used to define and convey the Solar System Mission and Technology Roadmap is hierarchical as shown in Figure 1-1. The fundamental goals or "Quests" provide the rationale for "Why we explore." "Campaigns" describe what we will study to achieve the "Quest"; they are focused scientific investigations. "Missions and Technologies" describe where we will go to answer specific questions that lead to the Quests, and what technologies

are needed to accomplish these tasks; they define the activities within each Campaign. "Research and Analysis" forms the base of the program, the scientific foundation upon which the whole activity is based. It is anticipated at the onset, that as our scientific knowledge changes, so will the details of the program. For this reason, the Roadmap should be viewed as a living document, responding to changes in our knowledge and capabilities.

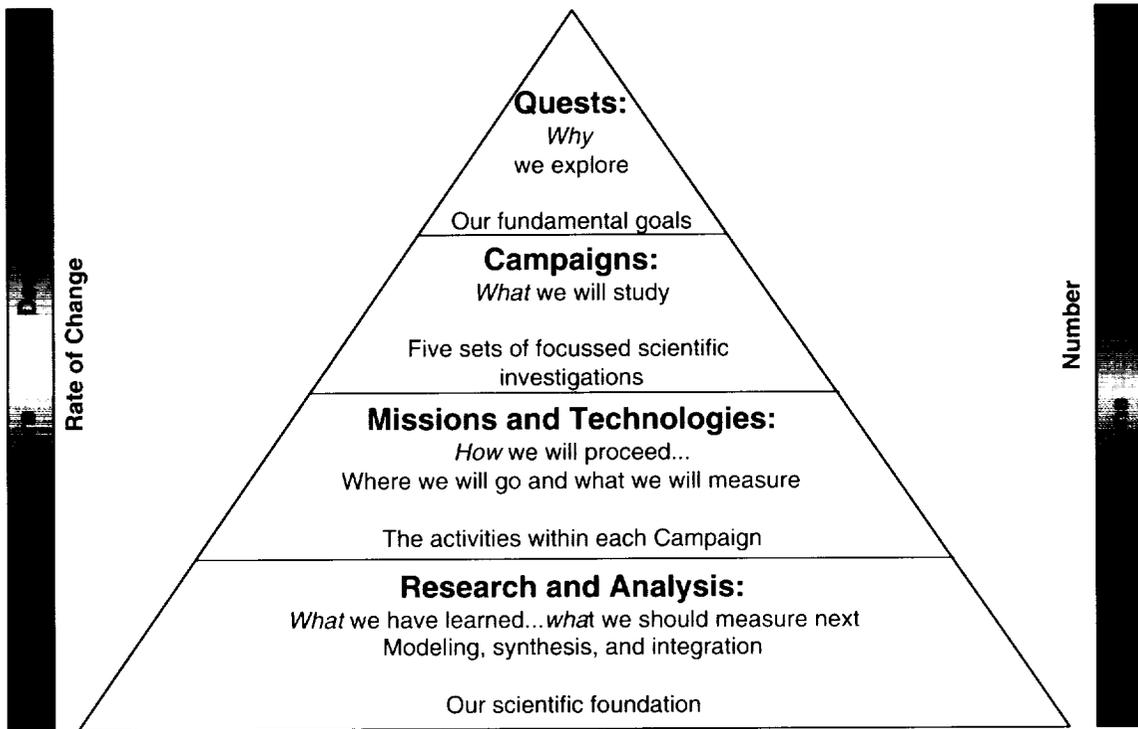


Figure 1-1: The hierarchical structure of the Solar System Mission and Technology Roadmap is illustrated using this pyramidal figure. The Roadmap starts with three long-term goals ("Quests") shown at the top of the pyramid. Five sets of focused scientific investigations ("Campaigns"), which lead to the Quests, are shown next. Specific activities including space missions and technology developments within each Campaign are shown below the Campaigns. "Research and Analysis" form the base of the pyramid and provide the scientific foundation for the Roadmap. The bar on the left gives a rough estimate of the rate of change of each level of the structure. The bar on the right shows the number of activities associated with each level.

CHAPTER 2

QUESTS AND INTELLECTUAL DESTINATIONS

A national space program must have broad public support as well as scientific and technological support in order to achieve balance. The Roadmap Development Team was chosen to achieve this balance, and its diverse interest groups have both overlapping and different reasons for why we explore the Solar System. Scientific reasons range from the desire to understand problems in physics, biology, and chemistry at the atomic and molecular levels, to understanding the Solar System as an entity in itself. Broader reasons include the sense of adventure, national pride, educational stimuli, technology drivers, and others. The first challenge of the Roadmap Development Team was to provide an overall structure for the study that cemented these groups together.

To bridge the gap between the diverse interests, the Roadmap Development Team initially focused discussions on where the Roadmap activities would lead in the long run; these discussions included underlying questions about the Universe, the Solar System, and humanity's place in it. Through these discussions, the Roadmap Development Team defined a set of three basic **Quests** for knowledge. The Quests provide the high level rallying points "Why we explore," and they establish the fundamental goals for the mission to the Solar System. Each Quest includes basic issues about the Solar System, and the history and future of life within it. The three Quests are discussed below.

2.1 QUEST 1: CHART OUR DESTINY IN THE SOLAR SYSTEM

The future of humanity depends on our knowledge and management of Solar System resources (Figure 2-1), especially those that affect the future habitability of Earth (Table 2-1). It is possible to learn a great deal about the Earth through intense study of this planet; however, to see how processes observed on Earth apply under different conditions, it is necessary to explore beyond Earth. We must explore each of the planets to determine their common and unique features, and use these similarities and differences to assist in interpreting the history of the Solar System. For example, when estimating the frequency of catastrophic impacts on Earth, we rely heavily on the study of cratering rates observed

throughout the Solar System. The study of planetary climates allows testing of ideas about terrestrial climates under different circumstances. (It is possible to learn a great deal by intense study of a single planet, however.)

The principal goals of Quest 1 are to:

1. Understand the Solar System forces and processes that affect the future habitability of Earth
2. Find extraterrestrial resources of human interest
3. Assess space frontiers suitable for future human exploration

Table 2-1 lists typical objectives that follow from each of these goals, and Figure 2-1 illustrates these objectives.



Figure 2-1: Typical objectives that flow from Quest 1

Table 2-1: Principal attributes of Quest 1—Chart our destiny in the Solar System

<p>The Future Habitability of Earth</p> <ul style="list-style-type: none">• Global climate change<ul style="list-style-type: none">– Venus-Mars-Earth: Divergence in evolution– The giant planets as weather laboratories– Titan: climate evolution on a terrestrial-type planet• Large impacts: History, frequency, prediction, effects<ul style="list-style-type: none">– Inventory near-Earth objects– Small-body composition, structure, and dynamics• Solar variations and planetary interactions <p>Extraterrestrial Resources</p> <ul style="list-style-type: none">• Accessible water and minerals on the Moon and Mars• <i>In situ</i> resource utilization: Opportunities, tools, techniques• Composition of near-Earth objects <p>Sites for Human Exploration</p> <ul style="list-style-type: none">• Moon and Mars: Global mapping, mineralogy, site reconnaissance
--

2.2 QUEST 2: EXPLAIN THE FORMATION AND EVOLUTION OF THE SOLAR SYSTEM AND THE EARTH WITHIN IT

An important question, basic to understanding both our past and future, concerns how the Solar System originated and evolved. To understand the Solar System, it is necessary to catalog the chemical and physical records existing today, especially in the primitive bodies and giant planets, which are thought to retain records of the conditions in the early Solar System. It is necessary to understand the processes that lead from molecular clouds to stars, planets, and planetary systems, and subsequently to the evolution of these bodies. These processes include behavior of gas and dust in interstellar space, magnetic fields, volcanism, and others.

The principal goals of this Quest are to:

1. Understand the origin of the solar nebula and the forces that formed Earth and the other planets
2. Determine the evolutionary processes that led to the diversity of Solar System bodies and the uniqueness of Earth
3. Use the other objects of our Solar System as natural science laboratories

Table 2-2 lists typical objectives that flow from each of these goals, and Figure 2-2 illustrates these objectives.

Table 2-2: Principal attributes of Quest 2—Explain the formation and evolution of the Solar System

Solar System Origin and Planet Formation

- Physical and chemical records: Primitive bodies and giant planets
- Collisional and dynamical processes in ring systems
- Behavior of dust and gas in interplanetary space

Evolutional Processes and Diversity

- Tectonics and volcanism: ancient and active
- Atmosphere formation, dynamics, and surface interactions
- Long-term impact histories
- Processes of compositional differentiation and crustal formation and evolution

A Natural Science Lab

- Large-scale atmospheric phenomena
- Magnetic fields, plasmas, and dynamos
- Evolution of structure in dynamical systems
- Properties of matter under extreme conditions

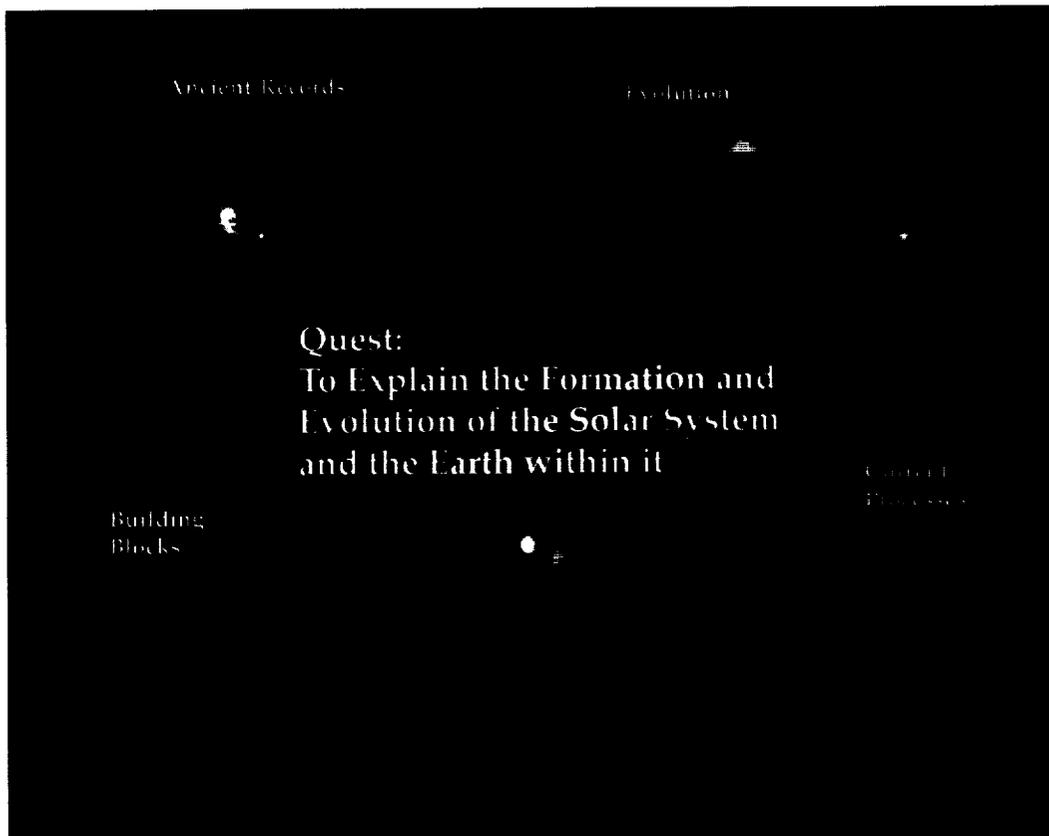


Figure 2-2: Typical objectives that flow from Quest 2

2.3 QUEST 3: SEEK THE ORIGIN OF LIFE AND ITS EXISTENCE BEYOND THE EARTH

The Quest to understand who we are and where we came from is universal. This Quest involves not only the search for extraterrestrial life, but also the search for clues as to how life on Earth began. To achieve this Quest, it is important to understand the history of water and organic materials on each of the planets and satellites. It is also important to understand the conditions that lead to life.

The principal goals of this Quest are to:

1. Understand the sources and reservoirs of water and organics—the building blocks of life
2. Determine the planetary conditions required for the emergence of life
3. Search for evidence of past and present life elsewhere in our Solar System

Table 2-3 lists typical objectives that flow from each of these goals, and Figure 2-3 illustrates these objectives.

Table 2-3: Principal attributes of Quest 3—Seek the origin of life and its existence beyond Earth

Water and Organics
<ul style="list-style-type: none">• Mars crustal water and organic chemistry• Ice and water in the outer Solar System• Cometary delivery of water and organics to the inner planets• A complete organics inventory
Conditions for Life
<ul style="list-style-type: none">• Active prebiotic chemistry• Defining the “zone of habitability”• Locating key elements, isotopes, and minerals
Evidence of Live
<ul style="list-style-type: none">• Chemical signatures: What to look for, where to look• Promising geological features: Where are the fossils?• Intensive Mars exploration and sample return

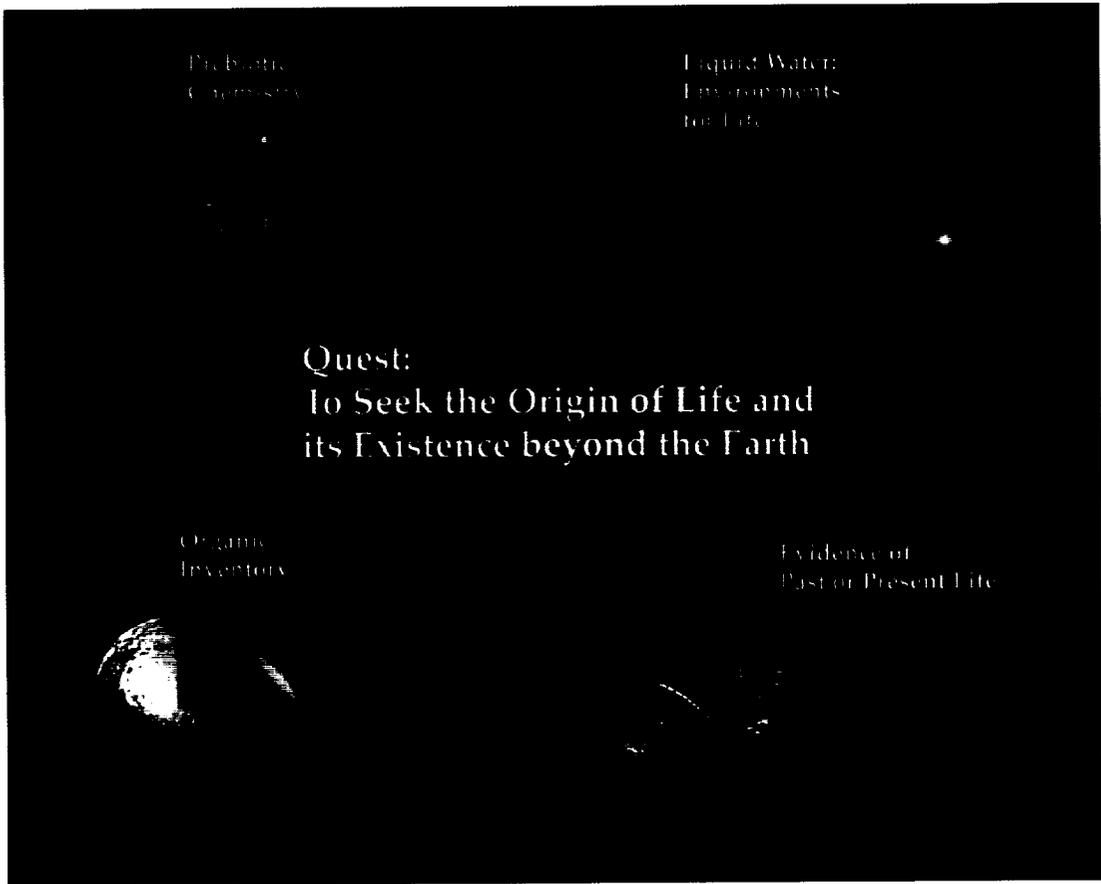


Figure 2-3: Typical objectives that flow from Quest 3

CHAPTER 3

CAMPAIGNS

The Quests discussed in Chapter 2 define fundamental goals and address the issues of why we explore; however, they do not address the scientific objectives, which in turn specify the mission architectures and instrumentation required to make progress toward the goals. The Roadmap Development Team concluded that focused scientific investigations addressing particular scientific areas of interest provided a good framework on which scientific objectives and approaches could be discussed. The Roadmap Development Team defined five sets of focused scientific investigations called Campaigns. Campaigns define *what will be studied* to achieve the goals of the Quests. They contain logical groupings of common missions and technologies. Campaigns contribute to the goals of at least one of the three Quests.

The five Campaigns emphasize the importance of trying to understand similarities of and differences between Solar System objects, rather than trying to understand individual objects in isolation. The five Campaigns are:

1. Building Blocks and Our Chemical Origins
2. Prebiotic Chemistry in the Outer Solar System
3. Formation and Dynamics of Earth-Like Planets
4. Evolution of Earth-Like Environments
5. Astrophysical Analogs in the Solar System

3.1 BUILDING BLOCKS AND OUR CHEMICAL ORIGINS

The purpose of the Building Blocks and Our Chemical Origins Campaign is to reveal the properties of the material from which the Solar System formed, and to determine how the present Solar System evolved from its nascent “solar nebula” to the early planets. Records of the composition and physical processes at the time of planet formation are preserved in comets, asteroids, meteoroids, giant planet atmospheres, and the Sun. The Campaign will inventory the basic physical, chemical, and isotopic properties of the diverse materials from which planets formed by exploring representative bodies with different physical conditions and from widely separated regions of the solar nebula.

As the planets were forming, smaller building blocks, or planetesimals, were scattered throughout the nebula, perhaps bringing volatiles (including water) and biogenic materials from the outer Solar System to the terrestrial planets. This model can be tested by studying the elemental, isotopic, molecular, and mineralogical compositions of comets and asteroids. Asteroid and comet studies will also reveal the violent collisional history of the growing terrestrial planets and yield an inventory of accessible space resources useful in future human exploration of the Solar System.

This Campaign will expand our understanding of these processes by studying the composition and structure of remnant planetary building blocks (comets and asteroids), as well as the large reservoir of volatiles from the solar nebula incorporated in the atmospheres of the giant planets. The Campaign should result in a completed survey of the Solar System, key information on the early Solar System and potential sources of organics and volatiles, and an inventory of resources for potential human exploration and hazards assessment. Figure 3-1 illustrates typical activities associated with this Campaign.

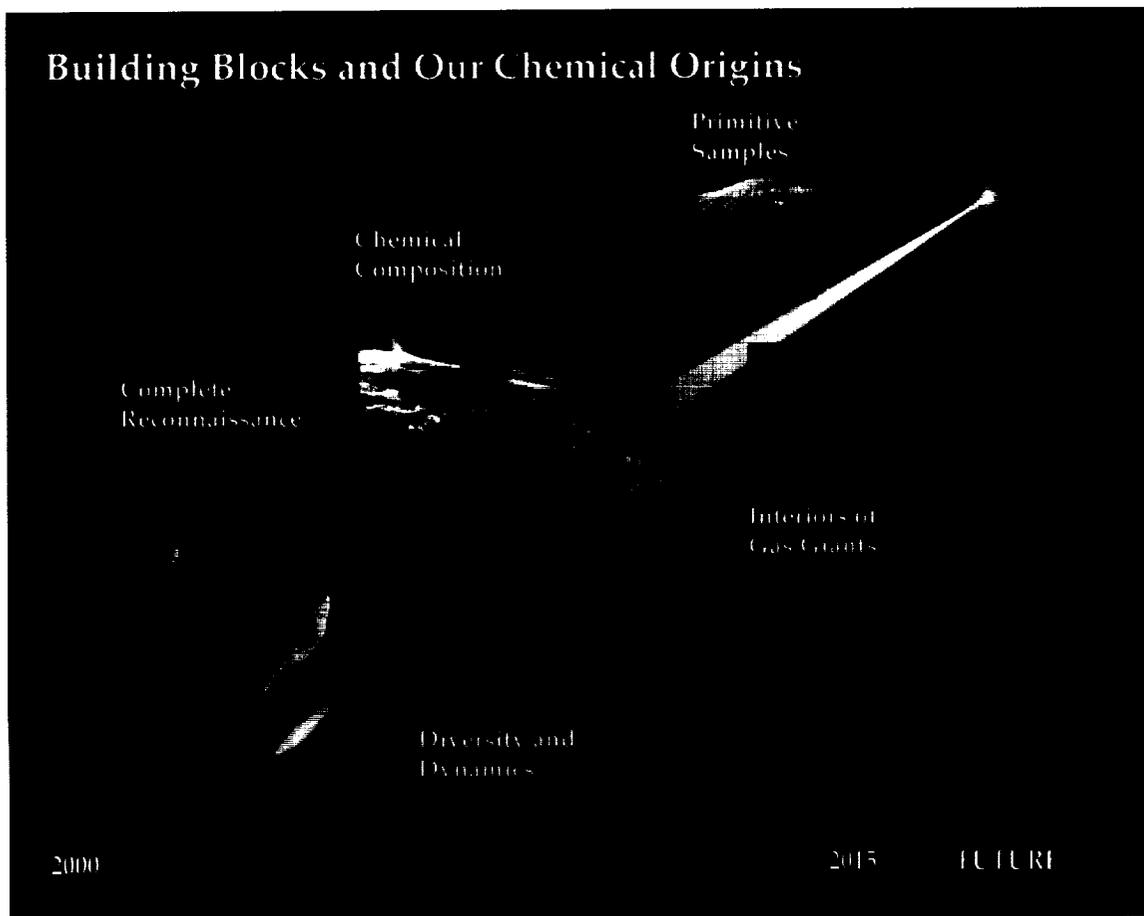


Figure 3-1: Activities associated with the “Building Blocks and Our Chemical Origins” Campaign

Our current knowledge of some of the more important Solar System objects related to this Campaign is summarized below:

Comets are believed to have been formed in the regions where giant planets were assembled, and perhaps beyond. Because they spend most of their time at a great distance from the Sun, they contain an unprocessed record of the primitive Solar System materials. Their volatile composition resembles that found in star-forming regions in the galaxy, but varies from comet to comet. Comets are volatile-rich and a potential source of water and prebiotic material on the early Earth. Impacts by comets on the Earth may have played a significant role in the evolution of life on Earth. Comets exhibit significant differences in their composition, which may reflect different formation regions in the presolar nebula, heterogeneous accretion, and/or subsequent processing. Comet collisions are still a potential hazard to Earth's inhabitants. The Kuiper Belt is an accessible repository of comet-like bodies and large bodies left over from planet formation. Pluto is a member of this belt.

Asteroids are a diverse population of Solar System objects, both in their location and their composition. Like comets, they are remnant building blocks from the formation of the Solar System. Most asteroids reside in the main belt between Mars and Jupiter at distances of 2.2 to 3.3 astronomical units (AU) from the Sun. Dynamical processes can move asteroids from the main asteroid belt into Earth-crossing orbits. Impacts by small bodies have played a significant role in the evolution of life on Earth, and asteroid impacts are another potential hazard to Earth's inhabitants. Asteroids have experienced a variety of processes, such as the heating in the early Solar System, which caused melting and differentiation, and the diversity of asteroid compositions can be correlated with their distance from the Sun. However, collisions are the dominant process affecting asteroids today.

Giant Planet Atmospheres, because of their strong gravity fields and relatively low temperatures, are a repository of primordial material. Complex organic compounds are found in these atmospheres, and isotopic compositions indicate that complex processing occurred both before and after Solar System formation.

The Sun now contains nearly all of the mass of the original solar nebula; consequently, solar composition is expected to define the average nebular composition from which planetary materials evolved. Unfortunately, current knowledge of the elemental composition of the Sun is rather poor (ranging from accuracies of $\pm 10\%$ to no data at all), while scarcely any isotopic abundances are known to the precision required for studies of Solar System evolution.

The Building Blocks and Our Chemical Origins Campaign has the following specific objectives:

1. Complete the reconnaissance of the Solar System
 - Flybys of Pluto and Kuiper objects as samples of icy material in their original preplanetary reservoir
 - Encounters with diverse comets and asteroids

-
2. Provide information on the composition of the early Solar System and potential sources of Earth's organics and volatiles
 - Primitive body exploration and sample return from comets and asteroids
 - Probes to deep interiors of giant planets
 3. Inventory resources for potential human exploration and possible hazards to planet Earth
 - Survey and explore the near-Earth objects

Possible missions within this Campaign are mentioned below and discussed in more detail in Chapter 4. A Pluto Fast Flyby mission was included in the Space Science Enterprise Strategic Plan for 1995.

- Pluto/Kuiper Express
- Primitive Body Explorers (Multi-Flyby Visitors, and a Large Asteroid Orbiter)
- Small Body Sample and Return
- Giant Planet Deep Probes

3.2 PREBIOTIC CHEMISTRY IN THE OUTER SOLAR SYSTEM

The Prebiotic Chemistry in the Outer Solar System Campaign seeks to identify and map the distribution of organic compounds, assay and understand details of organic chemical processes, and search for evidence of prebiological or protobiological activity on satellites of the gas giants. Europa and Titan, the two most likely sites for life, can be used as natural biological laboratories to understand how planetary environments can lead to life. Figure 3-2 illustrates activities related to this Campaign.

Europa, one of Jupiter's four major satellites, is a Moon-sized body. Its high albedo and spectral characteristics indicate the presence of surface water ice or frost. Galileo spacecraft observations indicate liquid water or even oceans under the surface. Water appears to be a critical precursor to life, and furthermore, internal heating of Europa by Jupiter's gravity may produce hydrothermal vents, similar to those on the terrestrial sea floor that support living communities by chemosynthesis rather than photosynthesis. Thus, detection and characterization of any Europa oceans is an integral part of our search for evidence of any life outside of Earth.

Titan, Saturn's largest satellite, has a thick nitrogen-methane atmosphere with a surface pressure 1.5 times that of the Earth. Laboratory simulations and Voyager data strongly suggest prodigious atmospheric organic chemistry powered by sunlight. The Cassini/Huygens mission will provide an initial survey of the nature of the surface and how the surface and atmosphere interact chemically. Then, advanced missions will provide detailed characterization of Titan's surface and atmosphere. These data may provide clues to the conditions on early Earth that led to the emergence of life.

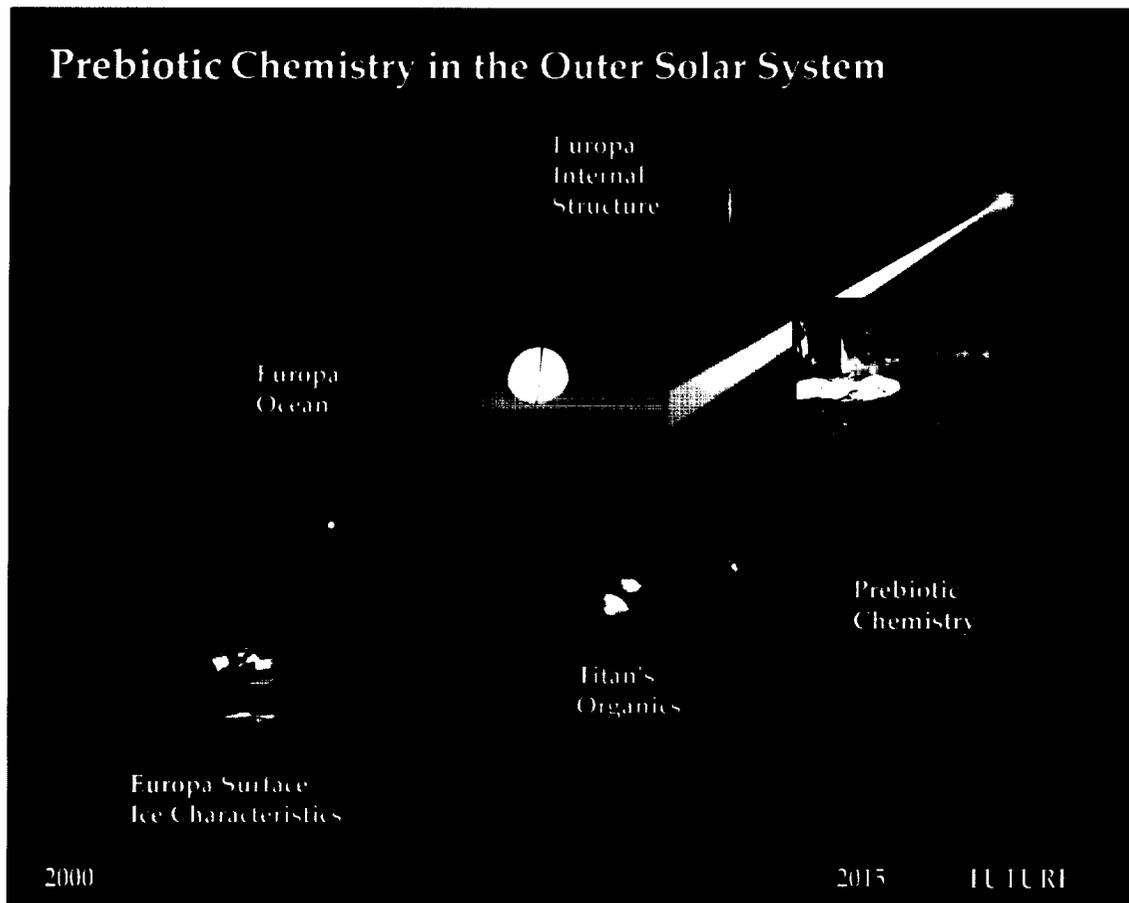


Figure 3-2: Activities associated with the “Prebiotic Chemistry in the Outer Solar System” Campaign

The Prebiotic Chemistry in the Outer Solar System Campaign has identified the following specific objectives for Europa and Titan:

1. Determine the nature of Europa’s surface and the origin of the ridges and other features on its smooth surface. Determine the surface ice thickness, and whether or not an ocean of liquid water lies beneath the ice. Determine the nature of any organic compounds present on the European ice surface, in the ice itself, and in the region below the ice.
2. Determine the detailed composition of organic compounds in Titan’s atmosphere. Identify and map the distribution of organic compounds on the surface of Titan. Determine the characteristics of organics on Titan’s surface, including a study to determine if these organics display any interesting prebiotic properties, such as the presence of amino acids or nucleotide bases, or of chirality (handedness).

Possible missions within this Campaign are noted below and described in Chapter 4.

- Europa Ocean Explorer
- Europa Landers
- Titan Organic Explorer
- Titan Orbiter
- Multiple Titan Probes or Mobile Titan Aerobot

3.3 FORMATION AND DYNAMICS OF EARTH-LIKE PLANETS

The Formation and Dynamics of Earth-Like Planets Campaign is based on the likelihood that many aspects of the formation and evolution of Earth are best illuminated by the study of our planetary neighbors. The Earth-like bodies of our Solar System are Venus, Mars, Io, Mercury, and the Moon. The rock-dominated bodies of the inner Solar System can provide records of periods of planetary formation no longer preserved here on Earth, and they can serve as comparative laboratories for understanding the basic physical processes that affect Earth. The earliest history of Earth, the period when all the planets were bombarded by the material left over from Solar System formation, is not preserved on our planet. However, the surfaces of the Moon and Mercury have been little modified over much of the age of the Solar System, and thus are excellent models for understanding the history of the early Earth. A second focus for this Campaign is understanding the dynamic processes that affect Earth-like planets and moons. Venus, with its abundant evidence of an active geologic past, Io, with its multitude of active volcanoes, and Mars all provide natural laboratories to expand our knowledge of processes that shape Earth, and that often represent significant hazards. As we look for other “Earths” beyond our own Solar System, this Campaign will allow us to refine our understanding of how Earth-like planets form by studying our own planet and its neighbors. Figure 3-3 illustrates a number of activities associated with this Campaign.

Each of the Earth-like bodies contains unique information that can help us to determine how Earth-like planets evolve. Earth-like bodies have gone through the process of differentiation to form crusts, mantles and cores, but differentiation took place at different times and in different proportions. If, as current theories suggest, the Moon formed after a large body impacted Earth, understanding the detailed chemistry of the Moon is critical to our understanding of the evolution of Earth. Earth-like planets show several types of magnetic fields, which give us clues to the state of planetary cores. The surface chemistry of Mercury will provide us with better knowledge on the process of planetary differentiation. Crusts of planets can continue to evolve, forming a secondary crust (the oceanic crust on Earth) and tertiary crusts (the continental crust on Earth). In general, the more evolved crusts mean the planet has been more geologically active. The Moon and Mercury have primary and secondary crusts, while Mars and Venus have secondary, and possibly tertiary, crusts. We need to understand the variability of surface compositions at Venus to constrain the evolution of its crust and understand how and why it differs from that of Earth.

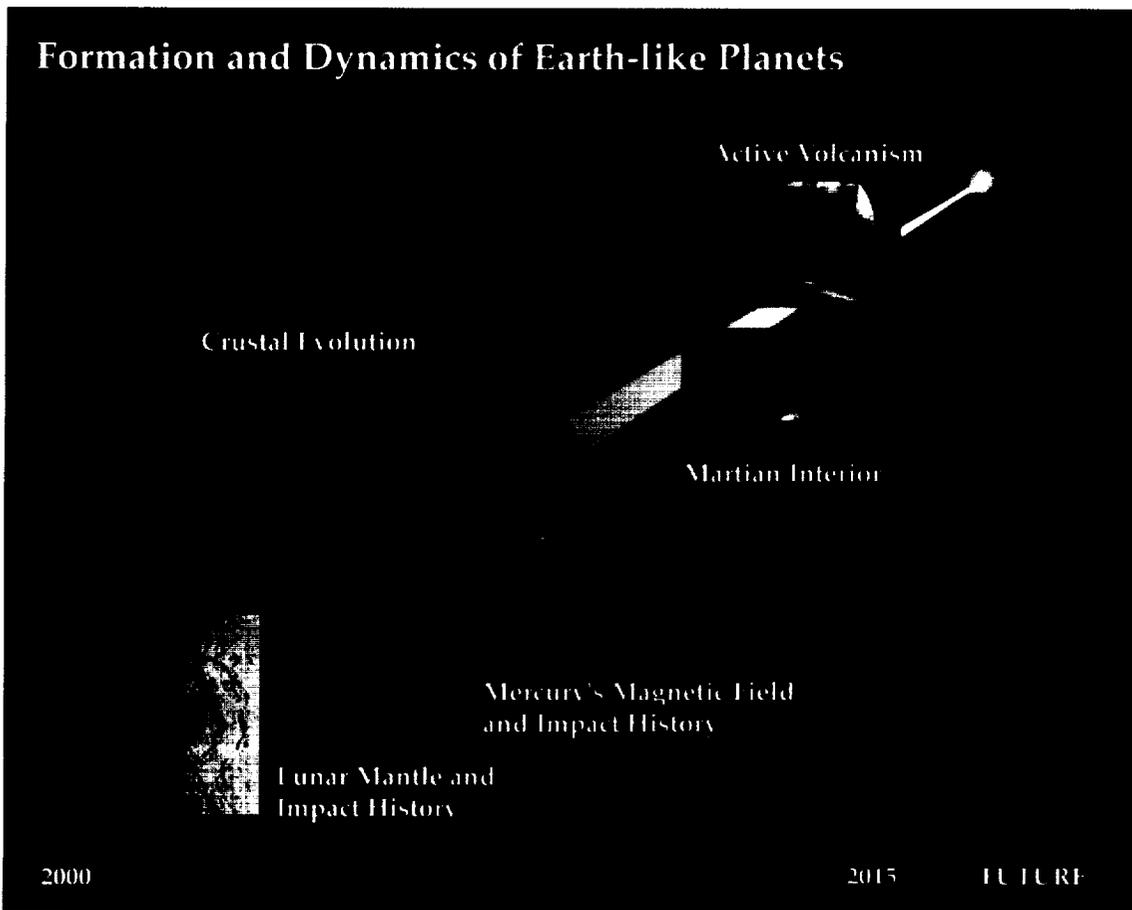


Figure 3-3: Activities associated with the “Formation and Dynamics of Earth-Like Planets” Campaign

Impact cratering, in particular the early bombardment, played a major role in early crustal formation and evolution (as well as atmospheric evolution) that is not fully understood. Mercury, with its uniquely high ratio of metal to silicate, may preserve important information on the competing effects of differential condensation, solar interaction, and giant impacts on planet formation in the Earth’s neighborhood. In addition, impact cratering has influenced biotic evolution on Earth, and perhaps on Mars. Both Mercury and the Moon provide data on the characteristics and effects of the early bombardment.

Volcanism and tectonism are important indicators of the internal thermal evolution of Earth-like planets. We know that volcanic activity was very important in the early history of all the bodies of the inner Solar System, both in terms of shaping the surface and affecting the atmospheric evolution. Io’s volcanoes can provide a testbed for understanding the physics of volcanic processes. We need to measure the compositions of volcanic materials at Io, and understand the dynamics and behavior over time of its volcanic eruptions. Venus may still have active volcanism, like Earth, but only Earth has active plate tectonics. Tectonic features on the Earth-like bodies formed at differing times from differing processes, ranging

from effects of planetary despinning at Mercury to the surface expression of interior convection at Venus. In addition, Venus may have undergone episodic thermal evolution and massive crustal overturn. We need to measure the frequency, locations, and duration of earthquakes (seismicity) on Venus, and to use the data to determine the interior structure of the planet.

Earth is unique in the inner Solar System in having an atmosphere presently dominated by nitrogen and oxygen—a place where life can flourish. Venus and Mars are dominated by carbon dioxide atmospheres, with Venus baking under a runaway greenhouse. We need to determine the composition of the Venusian lower atmosphere and its interactions with surface rocks. Mars, the only other inner Solar System body with significant water, appears to have had the potential to evolve life. Studies of Mars can help us better understand the evolution of climate, and potentially provide a place for future human habitation. Mercury, and perhaps the Moon, have polar anomalies that may be water ice, while the Venusian atmosphere contains some indications that the planet might have had an ocean very early in its history.

What can we learn by studying the Earth-like bodies?

If we study only one planet, we limit our ability to understand processes that have shaped our own planet over the last 4.5 billion years. Studying the surface chemistry and geologic history of Mercury and the composition and nature of the lunar mantle can help us understand the earliest stages of Earth's history. Studying crustal evolution by analyzing the surface chemistry on all the Earth-like bodies will help us better define how and when planets differentiate. Also, the degree of differentiation will help tell us how Earth-like planets are made. Studies of the inner planets will help better define how planetary interiors evolve, which interiors are active today, and how active they are. The levels of seismic activity on Venus and Mars are included in this study. Specifically, we can learn if Venus overturns its crust episodically and catastrophically, or if the planet behaves more uniformly through time like Earth. Volcanism, a process that represents a great hazard here on Earth, will be studied in a number of differing planetary environments to understand more about what controls the styles and timing of volcanic eruptions. Planetary studies over the past 35 years have already yielded important insights into the way the Earth works, as well as novel techniques for studying Earth itself.

What is the impact flux throughout Solar System history and recently on Earth? Impact flux estimate uncertainties greatly hinder our ability to understand the evolution of planetary surfaces. How do giant impacts work, and how do they influence the formation, composition, and evolution of atmospheres? Measuring the composition of the atmospheres of Venus and Mars and their interaction with surface materials will help us understand why planetary atmospheres diverged during their evolution, and may even tell how the Earth's atmosphere will evolve. The presence and state of water on the Earth-like planets is a critical issue that will be partially addressed by identifying the existence and composition of polar "ices" on Mercury and the Moon.

Future Missions

Future missions to the Earth-like bodies build upon knowledge gained from earlier missions such as the Mariner and Viking missions to Mars and the Magellan mission to Venus. Potential future missions within this Campaign are noted below and described in Chapter 4. Mars Surface Missions were included in the Space Science Enterprise Strategic Plan for 1995.

- Lunar Giant Basin Sample Return
- Mars Surface Network
- Venus Surface Mission (Landers and Aerobots)
- Io Volcanic Observer
- Mercury Orbiter

3.4 EVOLUTION OF EARTH-LIKE ENVIRONMENTS

Earth and its closest neighbors, Mars and Venus, share many similarities, yet each has had a dramatically different history. The Evolution of Earth-Like Environments Campaign seeks to understand these similarities and differences in terms of the processes that lead to each. Of the planets in our Solar System beyond Earth, Mars holds the greatest chance for having developed life. The crucial ingredient for life is liquid water. Thus, a key element of this Campaign is the history of liquid water on Mars (including its abundance, distribution, and cycling in the crust), and its role in sculpting the Martian landscape and modifying the long-term climate. For Venus, the Question of the early climatic history of the planet, the nature of the runaway greenhouse, and the possibility that water once existed on the Venusian surface provide additional fundamental focuses in this Campaign. Figure 3-4 illustrates a number of activities associated with this Campaign.

Mars

Mars has been volcanically active throughout its history, and the presence of lava flows that are completely free of impact craters indicates that eruptions may have occurred quite recently. Unlike Earth, there is no evidence of plate tectonics on Mars, and crater count ages suggest that most of the Martian surface is older than 3.0 billion years. Although liquid water is everywhere unstable at the surface, water-carved channels are in older Martian terrains, suggesting a warmer and wetter early climate than now and implying a denser atmosphere. Liquid water could be present currently in the subsurface of Mars (at depths of hundreds to thousands of meters). Geomorphic features on Mars formed by the activity of ground ice are widespread at higher latitudes (>40 degrees), indicating that the presence of subsurface water probably varies with latitude.

Elemental analyses obtained at the two Viking lander sites indicate that the Martian crust is comparatively enriched in iron and sulfur. We have measured major and minor components of the atmosphere of Mars, with isotopic analyses that indicate significant losses of the atmosphere to space. The similarity of deuterium-to-hydrogen (D/H) ratios

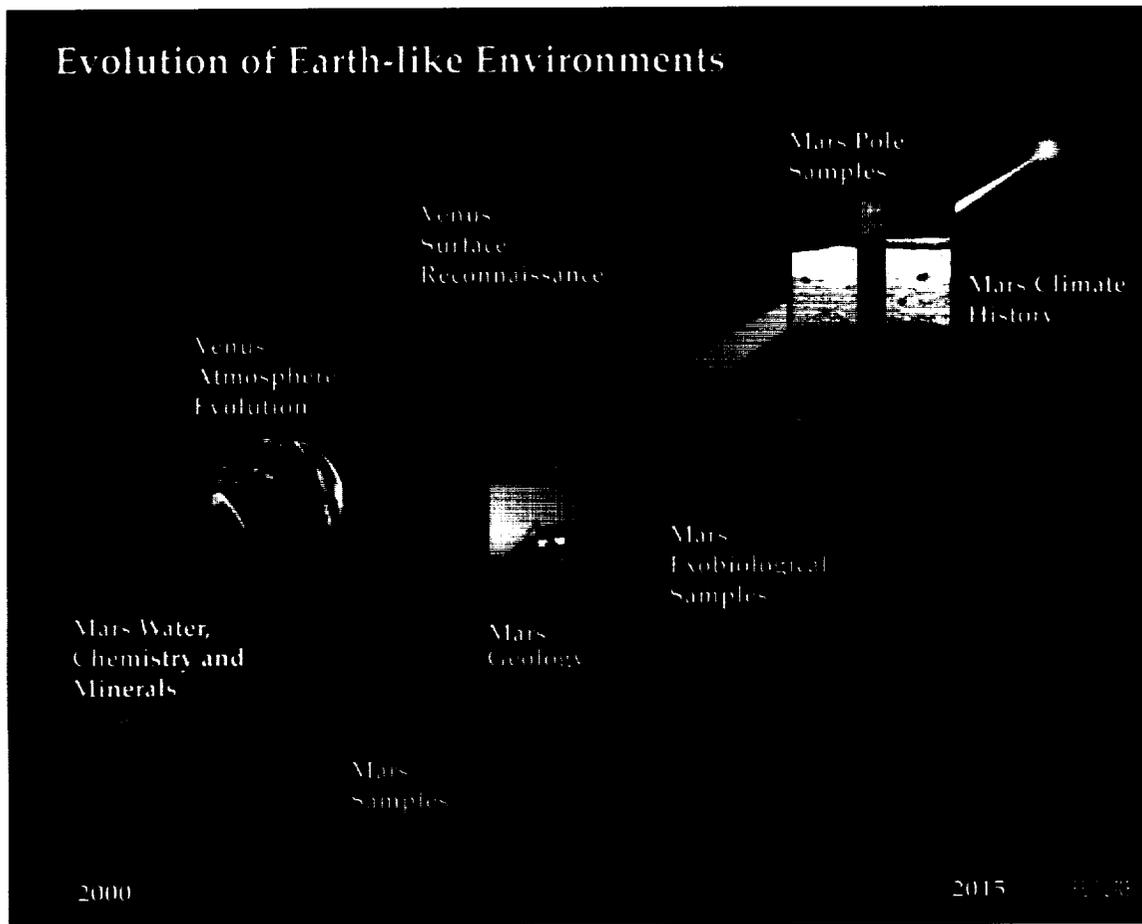


Figure 3-4: Activities associated with the “Evolution of Earth-Like Environments” Campaign

for water extracted from shergottite, nakhlite, and chassigny (SNC) meteorites that chemically appear to have come from Mars, and ratios from the atmosphere of Mars indicate that there has been an ongoing process of atmosphere-crustal exchange.

Results of the Viking biology experiments suggest that extant life is absent in surface environments on Mars. However, it could be present in deep subsurface environments where liquid water may exist. Furthermore, although the present surface of Mars is inhospitable to life as we know it, there is good evidence that the Martian surface environment was more Earth-like early in its history (3.5 to 4.0 billion years before present), with a warmer climate and liquid water at or near the surface. We know that life originated very quickly on the early Earth (perhaps within a few hundred million years), and it is quite plausible that life could have also emerged on Mars during the early window of opportunity when liquid water was present at the surface.

Major questions to be addressed at Mars regard the history of water, and other volatile compounds. This history is probably recorded in the rock and mineral deposits that make up the Martian crust. The next phase of exploration must initially address fundamental issues about the geologic history of Mars recorded in rocks. We need to know the

composition of the crust in detail, and specifically the minerals present. We must get beyond the limited, lander-based surface elemental analyses from Viking and Pathfinder and find out what minerals are present, as well as their abundances and distributions.

Particular minerals form under a fairly narrow range of conditions and geological environments. Thus, identifying particular mineral phases on Mars is the key to understanding past environments. The highest priority targets in the search for ancient life on Mars are aqueously deposited minerals such as carbonates, sulfates, nitrates, and hydrates. Such deposits are important repositories for signs of the existence of life (biosignatures) on Earth (e.g., organic compounds and/or microfossils) and are capable of retaining biological information for billions of years. These same mineral deposits are also the primary targets for studying the past climate and volatile history of Mars.

Venus

The composition of the present Venusian atmosphere has been studied using ground-based observations, as well as flyby spacecraft, orbiting spacecraft, and *in situ* measurements; however, large uncertainties still exist. Both major and minor components of the atmosphere of Venus have been measured, but there are large uncertainties in the altitude profiles. Current estimates of isotopic ratios indicate that significant losses of the atmosphere to space, particularly water, have occurred.

There is no evidence that liquid water could have existed on Venus within the past 300–500 million years. The presence of water on Venus in the past may be important to the evolution of the Venusian atmosphere to its current state. One hypothesis proposes that Venus had an early ocean which, over time, was depleted through a “runaway greenhouse” effect, with a monotonic decline continuing to the present. The current water budget in the Venusian atmosphere is about 30 ppm, and it is estimated that this inventory has a lifetime of 70–700 Ma, much less than the lifetime of the planet. The present atmospheric water may be in a steady state with the escape of water (or, more precisely, hydrogen) balanced by the influx of hydrogen in comets and the solar wind. However, there are problems with steady-state models related to the current deuterium-to-hydrogen concentration ratios.

The current D/H ratio is approximately 150 times that of Earth. Different processes remove hydrogen and deuterium from the Venusian atmosphere with varying efficiencies. These processes, thermal or nonthermal, typically depend upon collisions with other atoms or ions. The efficiency with which deuterium is removed relative to hydrogen, the fractionation factor, varies for different loss processes. Prior to August 1992, it was estimated that the overall fractionation factor for Venus was 0.012. Using this value and the current D/H ratio suggests that the atmosphere would have required 5 to 50 billion years to evolve through steady-state processes to its current state. This argues against steady-state processes for the simple reason that the Solar System has not been in existence that long. Recent reestimation of the fractionation factor increases it by tenfold to 0.13, providing for an evolutionary time-scale of 0.5 to 5 billion years, more consistent with steady-state processes. The source (or sources) of the Venusian atmospheric water must, however, have an eight-fold enrichment in the D/H content relative to typical terrestrial (inner Solar System)

materials. A suggested source is an early global ocean that was removed to the interior of the planet, early in its history, only to be steadily outgassed. Alternately, an outer Solar System source of comets or other bodies colliding with Venus could have the required D/H values.

Venera lander elemental analyses indicate that the Venusian surface is primarily basaltic; Magellan observations suggest a wide diversity of compositions. High-reflectivity regions on Venus may contain metallic minerals in a rock matrix, resulting from surface-atmosphere interaction.

A great deal of the uncertainty regarding the evolution of the Venusian atmosphere hinges on the poor understanding of the current atmospheric composition. Determination of the abundance and vertical profiles of water vapor, SO₂, CO, COS, H₂S, and sulfur vapor in the lower 20 km of the atmosphere of Venus is of the highest priority. The oxygen isotopic composition is also important. Confirmation of the vertical profile of water is very important. A knowledge of atmospheric composition in the lowest scale height (about 16 km), is directly relevant to the composition of the surface because the surface and the water vapor should be reacting with one another under the high temperature and pressure conditions present on Venus.

The following future missions to Mars and Venus are within this Campaign and are described in Chapter 4. Mars Surface Missions and A Sample Return Mission were included in the Space Science Enterprise Strategic Plan for 1995.

- First Mars Sample Returns
- Mars Water and Mineralogy Mapper
- Mars Mobile Science Labs
- Mars Geoscience Aerobots
- Advanced Mars Sample Return
- Venus Geoscience Aerobots

3.5 ASTROPHYSICAL ANALOGS IN THE SOLAR SYSTEM

Many planetary and astrophysical processes cannot be simulated in the laboratory because they involve very large spatial dimensions, extremely long time scales, high complexity, or other extreme characteristics unsuitable for laboratory experimentation. These processes must be studied directly in place or through the use of an analog in cases where scaling is not possible or uncertain. The Solar System itself provides accessible analogs to many phenomena that occurred in the early Solar System and that occur throughout the present-day Universe. The Astrophysical Analogs in the Solar System Campaign involves the study of bodies and structures in the Solar System to achieve two major goals: a) to provide a better understanding of the fundamental processes that led to the formation of the Solar System, and b) to seek insights on how the “Laws of Physics” are reflected in physical systems of radically different size.

Major questions that this Campaign addresses include the following:

What processes control changes in climate?

What are the feedback mechanisms between incident solar flux, atmospheric circulation, and atmospheric chemistry?

How do atmospheric dynamics and transport control/respond to climate change?

How are volatiles exchanged on diurnal, seasonal, and longer time scales? How sensitive are planetary climates to those variations?

What causes the diversity and dynamics of planetary atmospheres?

How does the composition of the gas giants vary with depth?

How do the structures of the gas giants depend on composition and dynamics?

How do phase transitions affect the distribution of chemical components in planetary interiors?

What drives the global circulation of the gas giant atmospheres?

What drives the global super-rotation of the Venus atmosphere?

How do sunlight, plasmas, gases, and solids mutually interact?

How does the interplanetary medium affect planets?

How do dusty, gassy plasma systems operate and evolve to produce the features observed in comet tails?

How can we predict the structure and dynamics of a magnetosphere?

How do natural dynamos work?

What are the high-order magnetic and gravitational fields of the gas giants and what processes can explain them?

What are the properties of matter under extreme pressure?

How can we explain the properties of planetary magnetic fields and their variations with time? Upon what planetary parameters do they depend?

How do planetary ring systems and their embedded satellites evolve?

What factors influence fine-scale dynamics in planetary rings?

What are the relationships between the outer planet satellites and the ring systems in which they are embedded?

What causes the diversity of satellite families?

The Campaign aims to explore a diverse collection of objects which, for purposes of organization, are placed in four major theme (or activity) areas. The four major themes (see Figure 3-5) are:

1. Structures and dynamics of atmospheres
2. Sun/plasma/gas/field/solid interactions
3. Planetary and satellite dynamos
4. Ring systems

3.5.1 *Structures and Dynamics of Atmospheres*

The similarities and differences in the dynamics and circulations of different planetary atmospheres provide a context in which to understand the behavior of Earth's atmosphere.

The Venusian atmosphere is strikingly different from Earth in structure, composition, solar energy deposition, and planetary rotation rate. There is little similarity in their global atmospheric circulations and dynamics. A detailed explanation of Venus' global atmospheric circulation remains a major challenge.

The zonal flows in the atmospheres of the four giant planets are measured to be as large as hundreds of meters per second, but there is as yet no accepted theory for their origin, or even for their behavior as a function of latitude. Cassini will improve this situation greatly for Saturn by refining measurements of the mean zonal flow while also determining the flux of eddy momentum and heat in an effort to measure the energy input into the zonal flows. However, the behavior of the zonal flows with depth in the atmosphere—an all-important dynamical quantity—will still be unavailable from Cassini remote-sensing observations.

At the low temperatures prevailing in giant-planet atmospheres, hydrogen molecules separate into two almost-distinct quantum species, with a slow conversion from one to the other and an associated latent heat. Investigation of the relative abundances of the two species by entry probes will provide better information about the conversion process and its role in generating the large-scale flows and temperature fields seen in these bodies. At the same time, measurement of flow patterns at deep levels in the atmosphere will tell us if these flows are superficial or extend deep into the interior, as is currently believed to be the case.

There are two models for the phase diagram of hydrogen at high pressure: One predicts a so-called "plasma phase transition," or fundamental change in the structure of the hydrogen, and the other does not. If the phase transition exists, it will profoundly modify the abundances of trace species in the dense hydrogen fluid. Measuring the composition of the deep atmospheres of giant planets will help clarify this important problem of physics and chemistry.

3.5.2 *Sun/Plasma/Gas/Solid Interactions*

The comas and tails of active comets tell us about the interactions between sunlight, gas, plasma, and dust grains that occurred in the solar nebula and still occur in a wide range of astrophysical settings.

The structure and dynamics of diverse planetary magnetospheres reveal how flowing plasmas interact with magnetic fields under a variety of conditions. These processes are related to phenomena such as geomagnetic activity, pulsars, x-ray bursters, and radio galaxies.

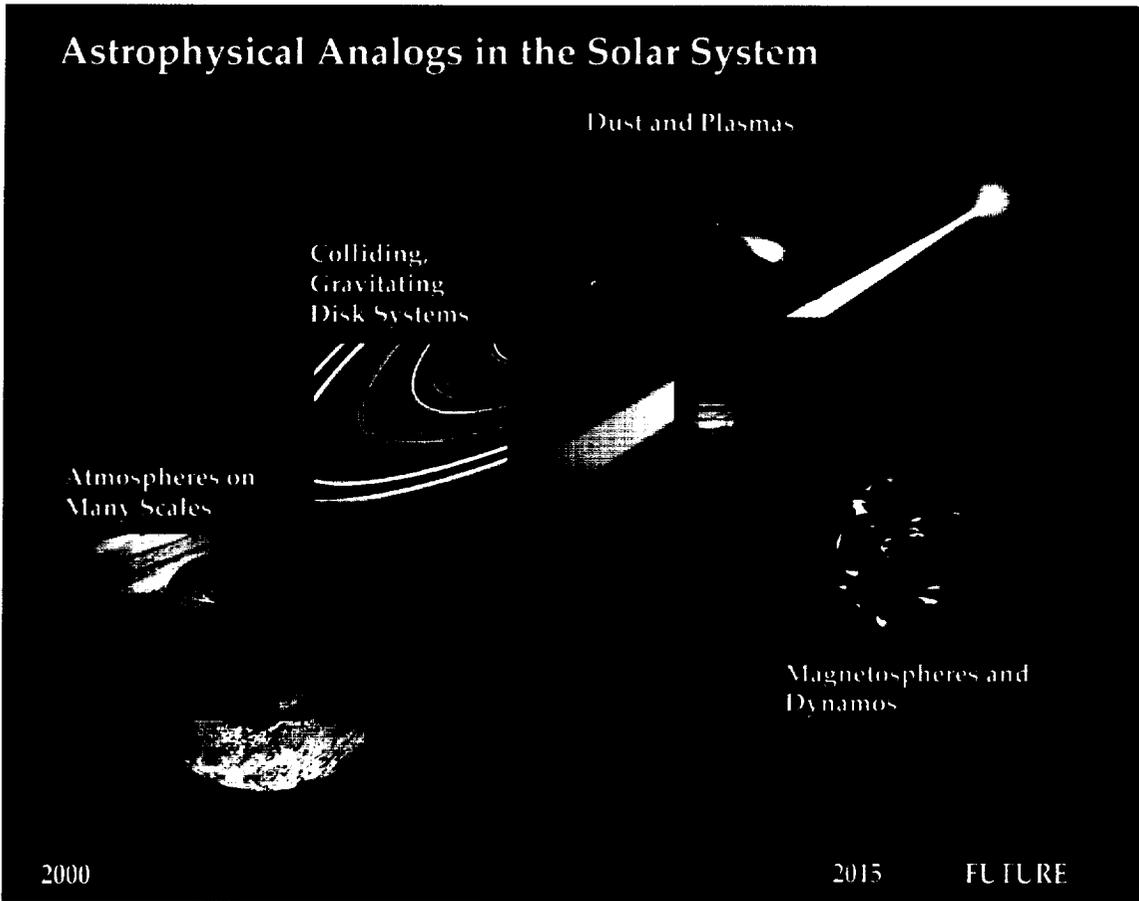


Figure 3-5: Four major activities associated with the “Astrophysical Analogs in the Solar System” Campaign

We have some knowledge of the magnetospheres of all planets (except Mars and Pluto) as well as active comets and some asteroids. We also understand the reasons for the major differences between them. Each magnetosphere exhibits dynamic behavior that produces phenomena such as auroras.

The mechanisms of these phenomena are not well understood. For instance, several theories have been advanced to explain the spokes in Saturn’s rings. In another poorly-understood case, Jupiter’s magnetosphere apparently “spits out” bursts or streams of dust particles.

3.5.3 Planetary and Satellite Magnetospheres and Dynamos

We have measured (with the exception of Pluto), but cannot explain, the strengths and directions of all planetary magnetic fields. We do not understand why the Earth has a strong dynamo while Mars and Venus do not. We have data on the time variations of the Earth’s and the Sun’s magnetic fields, but little knowledge about variations in other Solar

System bodies. We may be able to learn how natural dynamos work by studying the diversity of planetary and satellite magnetic fields.

Basic data on the composition of giant-planet atmospheres indicate that they are primary reservoirs of primordial hydrogen-rich gas, with their structure and dynamics strongly affected by the quantum behavior of hydrogen at relatively low temperatures and high pressures. There is evidence that minor species partition in subtle ways within various forms of hydrogen. The phase diagram of hydrogen, the simplest element, is proving to be extraordinarily complex, and studies of the giant planets will help to elucidate it. The interior structure is probably intimately related to the formation of dynamos.

3.5.4 *Ring Systems*

The study of planetary rings provides unique insights into the collisional and dynamical processes that led to the formation of the Earth and the other planets, and the forces that currently sculpt and shape spiral galaxies.

All four gas giant planets possess ring systems, replete with complex structures and phenomenology. A handful of ring features are understood in terms of dynamical perturbations from known satellites, both external and internal to the ring system. But the vast majority of ring features have no acceptable explanation. Furthermore, we do not yet have a good understanding of the qualitative differences between these systems, nor do we reliably know their ages or their origins. There are indications that ring systems are, in general, not primordial, but this assessment rests on some very poorly determined quantities related to the nature of the particles and the collisional environment in which they are embedded. Cassini can be expected to contribute to all areas of ring science—composition, kinematics, dynamics, searches for embedded satellites, particle size distribution—but many results will be inferential. For lack of spatial resolution on the rings, it will not provide a direct look at the physical properties of ring particles and the manner in which they interact.

3.5.5 *Astrophysical Analogs Specific Objectives*

The Astrophysical Analogs in the Solar System Campaign has identified the following specific objectives for this Campaign.

Atmospheric Dynamics: Refine measurements of mean zonal flow and determine flux of eddy momentum and heat on Saturn. Obtain a better understanding of the atmospheric structure and circulation of Neptune. Obtain better information about the phase changes of hydrogen and its role in generating large-scale flows and temperature fields in the gas-giant planets. Determine how deep the flows extend down into the interior of all the gas-giant planets.

Sun-Plasma-Gas-Dust Interactions: Determine time variability of Mercury's magnetosphere. Obtain better understanding and prediction of geomagnetic disturbances

at Earth and other planetary and astrophysical bodies. Obtain insight into how gas and dust interacts with the magnetosphere at Jupiter.

Dynamos: Obtain insight into how magnetic fields of Jupiter, Mercury, and Neptune are produced and how natural dynamos work. Measure changes in Jupiter's magnetic field over decades.

Ring Systems: Directly measure physical and collisional properties of ring particles in Saturn's rings. Determine the rate of angular momentum flow through Saturn's rings. Improve our understanding of the evolution, lifetime, and origin of Saturn's rings. Determine the relationships between rings and satellites for Neptune. Test whether satellites were tidally dragged into the ring region, with the ring system forming afterwards. Obtain insight into geological and dynamical histories of Neptune's satellites. Determine distribution of mass in Neptune's ring system and its dynamical relationship to the satellites.

Potential missions within the Astrophysical Analogs in the Solar System Campaign are listed below and described in Chapter 4:

- Outer Planet Multiprobes
- Jupiter Polar Orbiter
- Neptune Orbiter with Triton Flybys
- Saturn Ring Observer
- Mercury Magnetospheric Multi-Satellites

CHAPTER 4

ROADMAP MISSIONS

This Solar System Roadmap activity identified 24 example missions that can address Campaign objectives during the years 2000–2015. Table 4-1 lists these missions, and Figures 4-1 through 4-24 supply details about each individual mission. The example missions listed here are intended to be used as reference materials in the Space Science Enterprise planning process. The example missions provide a focused measurement strategy to meet the Campaign objectives, and they help identify future technology needs. Each of the missions can use a Delta-class or smaller launch vehicle.

Individual missions are believed to be affordable under current budget projections; however, the mission set as a whole is larger than the current budget can support. The mission set was made intentionally larger in order to provide a broad perspective on mission possibilities and to allow for prioritization by the scientific community. Missions chosen to meet Campaign objectives will be selected as part of the Space Science Enterprise planning process. Factors affecting selection will include: (a) programmatic considerations and budgets; (b) new scientific discoveries and analyses expanding our understanding of the Solar System; (c) technology availability; and (d) international opportunities.

Table 4-1: Roadmap missions listed under the Campaign each supports

Building Blocks and Our Chemical Origins	Evolution of Earth-Like Environments
Pluto/Kuiper Express	First Mars Sample Return
Multi-Body Visitors	Mars Water & Mineralogy Mapper
Large Asteroid Orbiter	Mars Mobile Science Labs
Small-Body Sample Return	Mars Geoscience Aerobots
Giant Planet Deep Probes	Advanced Mars Sample Return
	Venus Geoscience Aerobots
Prebiotic Chemistry in the Outer Solar System	Astrophysical Analogs in the Solar System
Europa Ocean Explorer	Outer Planet Multiprobes
Titan Organic Explorer	Jupiter Polar Orbiter
Europa Landers	Neptune Orbiter w/Triton Flybys
Formation and Dynamics of Earth-Like Planets	Saturn Ring Observer
Lunar Giant Basin Sample Return	Mercury Magnetospheric Multi-Sats
Io Volcanic Observer	
Mars Surface Network	
Venus Surface Mission	
Mercury Orbiter	

A number of the missions similar to those listed in Table 4-1 were mentioned previously in the Space Science Enterprise Strategic Plan in 1995. Near-term Programs mentioned in that Plan included a Mars Surveyor Program composed of a series of Mars landers instrumented with a new generation of miniaturized science instruments for a wide variety of surface and subsurface investigations, and a sample return mission. A Pluto Express mission was identified. Scientific goals for this mission included comparing the Titan–Triton–Pluto triad, studying Pluto’s atmosphere, studying the chemistry of the outer solar nebula, and studying the formation of the unique Pluto–Charon binary system. Multiprobe missions to Venus were identified for measuring detailed wind and temperature profiles.

Brief discussions of each mission are given below. Figures 4-1 to 4-24 characterize each mission by its science objectives, mission description, measurement strategy, and technology strategy. The missions are listed in the order they are given in Table 4-1; no prioritization is intended.

1. ***Pluto/Kuiper Express***—This mission will complete the reconnaissance of the Solar System with flybys of Pluto, Charon, and one or more Kuiper Belt objects. Pluto is the most poorly understood planet in our Solar System and may be the largest member of the primitive Kuiper Belt. This mission will provide the first closeup of Pluto’s surface and atmosphere. Gross physical and chemical surface properties of Pluto, Charon, and Kuiper Belt objects will be studied.
2. ***Multi-Body Visitors***—Comets and asteroids are known to show great diversity from object to object. This mission will provide encounters with 4–5 asteroids and 2–3 comets. Compositional diversity will be studied, and an attempt will be made to understand the different evolutionary paths that led to the diversity among these objects.
3. ***Large Asteroid Orbiter***—This mission will focus on a large main belt asteroid such as Ceres, the largest known main belt asteroid with a radius of ~385 km. Collisional history, internal structure, and chemical composition will be the primary science objectives.
4. ***Small Body Sample Return***—Comet and asteroid sample return missions are necessary to understand the initial conditions and evolutionary history in the solar nebula. This mission will provide core samples from comets and asteroids for analysis in terrestrial laboratories.
5. ***Giant Planet Deep Probes***—Because of their large gravity and relatively low temperatures, the interiors of the giant planets are believed to be reservoirs of presolar nebula materials. Deep probes of giant planets will measure the bulk composition and diversity between the planets, and will study deep atmosphere dynamics.
6. ***Europa Ocean Explorer***—Both theoretical considerations and observational data from Galileo suggest that Europa might have subsurface liquid water beneath its ice-covered surface. A Europa Ocean Explorer will measure the global water-ice thickness and search for liquid water. If liquid water is found, subsequent missions will search for molecules indicating life at various stages, either extinct, existing, or developing.

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7. ***Titan Organic Explorer***—Saturn’s largest satellite, Titan, has been known for over 50 years to have methane in its atmosphere. Voyager found the atmosphere of Titan to be suitable for the production and retention of prebiotic organic material; Cassini/Huygens will explore the chemistry further. The Titan Organic Explorer will measure the distribution and composition of organic material on the surface and in the atmosphere, and it will search for evidence of prebiological or protobiological activity.
 8. ***Europa Lander***—The Europa Lander will conduct *in situ* measurements of surface ice thickness and composition. It may also probe into the ice to determine its properties at depths. It is possible that water flows or subsurface water may also be sampled directly.
 9. ***Lunar Giant Basin Sample Return***—The many samples returned from Apollo have allowed us to determine much of the history of the Moon. However, the lunar mantle has remained unsampled. Giant impacts into the lunar surface caused material from the mantle to be exposed at the surface in a few very large basins, including the South Pole Aitken Basin on the lunar far side. Samples returned from this basin will allow chemical study of the lunar interior and will provide significant constraints on models of the origin and evolution of the Moon, as well as information on the early Earth.
 10. ***Io Volcanic Observer***—Io may be the most volcanically active body in the Solar System. To understand the morphologies, dynamics, and compositions of eruptions on Io, a long-lived orbiting satellite is required.
 11. ***Mars Surface Network***—Point measurements on planetary surfaces provide an important initial characterization of a body. However, as one measurement of the Earth’s climate in Southern California would not provide much real information on the dynamics of the Earth’s climate, so measurements taken at one planetary location do not characterize planet-scale processes. On Mars, a global network of as many as 16 stations will collect meteorology and seismic data to begin to fully characterize the martian climate and the state of the planet’s interior.
 12. ***Venus Surface Mission (Landers and Aerobots)***—Our next challenge on the study of Venus is to gain access to the lower atmosphere and the surface for sophisticated mineralogy and compositional measurements. Detailed measurements on surface mineralogy, lower atmospheric composition, seismic data, and meteorological data are critical in understanding the divergent path that Venus has taken from Earth. Both aerobots and long-lived surface stations represent technological challenges that must be solved to address significant science questions at Venus.
 13. ***Mercury Orbiter***—Next to Pluto, Mercury is the most poorly understood planet in our Solar System. We have seen only 45% of its surface, and know very little about its surface composition. Mercury can provide significant constraints on models of planetary differentiation and, with its unusual highly metallic composition, provide information on the nature of planetary interiors.

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14. ***First Mars Sample Return***—This mission will return samples from the Martian surface for studies in Earth-based laboratories. Mineralogical and elemental analysis of soil, and possibly of rock, will be performed. The mission will demonstrate systems for future Mars sample return programs.
 15. ***Mars Water and Mineralogy Mapper***—The first milestones for future missions to Mars will be the identification of aqueous sedimentary deposits and water (ice) on Mars and an understanding of their global distribution gained from orbital remote sensing data. This mapping will help to identify locations of the highest-priority targets i.e., locations that will answer questions about the early Martian environment and, potentially, life. These investigations will also form a basis for selecting the highest-priority sites for landed missions and sample returns.
 16. ***Mars Mobile Science Labs***—This mission will include a 1–10 km range rover with a lifetime of one Mars year. Regional geochemistry and geology will be investigated. Site selection for future sample return missions will be identified.
 17. ***Mars Geoscience Aerobots***—High spatial resolution (i.e., 100 m/pixel or less) spectral mapping from balloon (aerobot) platforms of key sites will be performed. A broad reconnaissance activity will be carried out to search for optimum sites for exobiologic sample return.
 18. ***Advanced Mars Sample Return***—This advanced mission will search for past or present life on Mars. It will return a diverse set of sample materials (rocks, soil, and atmosphere) to Earth for further analysis.
 19. ***Venus Geoscience Aerobots***—The deep atmosphere and surface of Venus are extremely difficult to explore because of the high pressures, high temperatures, and caustic nature of the atmosphere. An advanced technology Venus aerobot, using vertical altitude control and zonal wind patterns for horizontal motions, will study the composition and dynamics of the lower atmosphere. Surface mineralogy and geochemistry will be explored.
 20. ***Outer Planet Multiprobes***—Outer planet multiprobes will be deployed to Neptune, Saturn, Jupiter, and Uranus (priority order) to understand the diversity of outer planet atmospheres including structures, dynamics, and global circulation.
 21. ***Jupiter Polar Orbiter***—Measurement of the detailed structure of the magnetic field of Jupiter, and its relation to the detailed structure of the gravitational field and internal structure will provide insight into how the fields are produced and how natural dynamos work. There are prospects for detecting changes in Jupiter’s magnetic field over periods of decades, the expected time scale for hydromagnetic variations in the planet’s deep interior. Measurements of the atmospheric circulation at polar latitudes should also lead to a better understanding of the circulation of the Jovian atmosphere.

-
22. *Neptune Orbiter with Triton Flybys*—Neptune’s ring system contains unique clues to a key question in the study of rings: what is the relationship, both in evolution and at present, between rings and satellites? The Neptune system is unusual in that relatively large satellites are found orbiting among the rings, deep within the Roche zone where tidal forces might be expected to tear the moons apart. Close-range and long-term study of the ring and satellite system from a Neptune orbiter will allow us, through imaging and compositional mapping of the surfaces of these satellites as well as the rings, to investigate different hypotheses. Active weather on Neptune, its high relative heat flow and quiescent magnetosphere, and unique seasonal changes on Triton all combine to make this an important mission.
 23. *Saturn Ring Observer*—A mission deliberately designed to study the breadth of Saturn’s rings with a resolution of 1 meter will answer many of the questions that will undoubtedly remain after Cassini. Particles within Saturn’s rings range from dust-sized to approximately 5-m in radius; the larger particles in this distribution are the most dynamically important. Imaging of ring particles and their collisional interactions will provide direct measurement of their physical and collisional properties. From these quantities one can immediately determine the rate of angular momentum flow through the rings and, therefore, ring evolution and lifetime.
 24. *Mercury Magnetospheric Multi-Sats*—Study of the expected rapid changes in Mercury’s magnetosphere may lead to better understanding and prediction of geomagnetic disturbances on Earth and other planetary and astrophysical bodies. Multiple satellites (multi-sats) in orbit will allow simultaneous and diverse observations of the solar wind, the magnetosphere, and Mercury itself.

PLUTO/KUIPER EXPRESS

SCIENCE OBJECTIVES

- First characterization of Pluto and Charon
- Global geology and morphology
- Surface composition mapping
- Structure and composition of neutral atmosphere
- First encounter with Kuiper object
- Possible Io encounter during Jupiter flyby



MISSION DESCRIPTION

- Two small “sciencecraft” with mass ~100 kg each
- Delta II or Molniya launch vehicles
- Flight time: 10–13 years using multiple gravity assists

MEASUREMENT STRATEGY

- Remote sensing: Imaging, IR mapping spectrometer, UV spectrometer
- Uplink occultation experiments
- Pluto atmospheric “drop zone” (Russian collaboration option)

TECHNOLOGY STRATEGY

- Aggressive mass reduction: Microelectronics, telecom, power, propulsion
- High-efficiency radioisotope power source
- Extensive spacecraft autonomy including “beacon-mode” cruise
- Robust, long-life spacecraft systems

Figure 4-1: Roadmap Mission: Pluto/Kuiper Express

MULTI-BODY VISITORS

SCIENCE OBJECTIVES

- To understand the nature and origin of the compositional diversity of comet nuclei and asteroids
- To understand the nature and origin of different evolutionary states in comet nuclei and asteroids



MISSION DESCRIPTION

- Heliocentric orbit selected to provide multiple flybys with desired objects
- Earth gravity assist may be used to enable additional encounters
- Delta or med-lite launch
- Mission options include 2–3 comet encounters or 4–5 asteroid encounters during 4–5 year mission

MEASUREMENT STRATEGY

- Imaging and spectrometry
- Radio science for mass determination
- Possible *in situ* chemistry studies using impactors

TECHNOLOGY STRATEGY

- Autonomous navigation and target acquisition
- Advanced solar power systems
- Impactors and impact flash spectroscopy techniques

Figure 4-2: Roadmap Mission: Multi-Body Visitors

LARGE ASTEROID ORBITER

SCIENCE OBJECTIVES

- Detailed global characterization of a large main-belt asteroid
- Chemical composition and mineralogy
- Collisional history
- Internal structure

MISSION DESCRIPTION

- Reference target: Ceres
- Delta-class launch of approximately 150 kg spacecraft
- Flight time 2–3 years
- 1 year in Ceres orbit; 10–100 km altitude



MEASUREMENT STRATEGY

- Imaging and spectrometry of entire surface
- Higher resolution imaging of selected features and impact sites
- Radio science investigations of internal structure
- Fields and particles studies
- Possible *in situ* chemical analysis using penetrator/lander

TECHNOLOGY STRATEGY

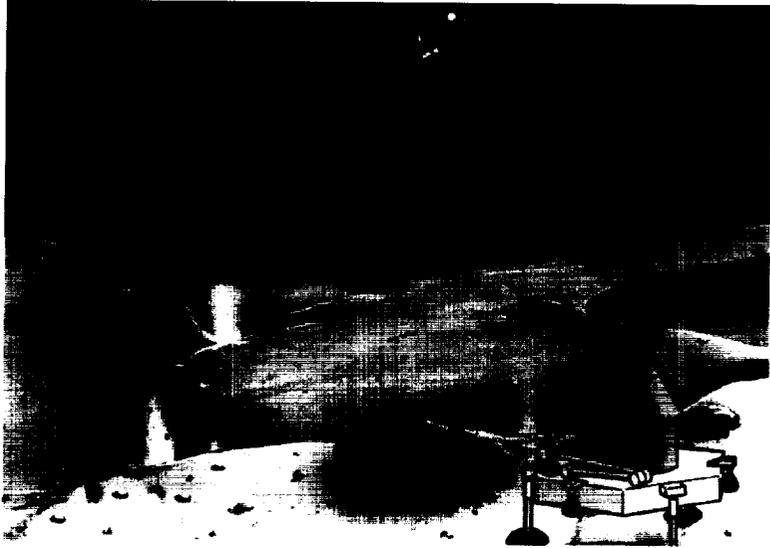
- Advanced solar arrays
- High-efficiency chemical propulsion
- Autonomous navigation and feature tracking
- Penetrator/lander technology

Figure 4-3: Roadmap Mission: Large Asteroid Orbiter

SMALL BODY SAMPLE RETURN

SCIENCE OBJECTIVES

- Long-term sample return series: Comets and asteroids
- Variety of comet/asteroid types, multiple sampling sites
- Subsurface sampling
- Laboratory study of primitive material, organics, and minerals in comets and asteroids



MISSION DESCRIPTION

- Delta-class launch vehicles, flight times 4–6 yrs
- Options for single spacecraft, or separable subspacecraft for descent, sampling, and rendezvous with return vehicle
- Advanced solar-electric propulsion (SEP) or solar sail enables sampling multiple targets with a single launch

MEASUREMENT STRATEGY

- Imaging/spectrometry for site selection and characterization
- Subsurface sampling using coring penetrator and tether system or surface drills
- Sample size ~0.5 kg per target

TECHNOLOGY STRATEGY

- High-efficiency solar arrays
- Autonomous control and navigation near low-gravity bodies
- Various sample acquisition and handling systems for different target types and surface or sub-surface sampling
- Advanced lightweight propulsion (SEP or solar sail) greatly enhancing performance and/or reducing flight time

Figure 4-4: Roadmap Mission: Small Body Sample Return

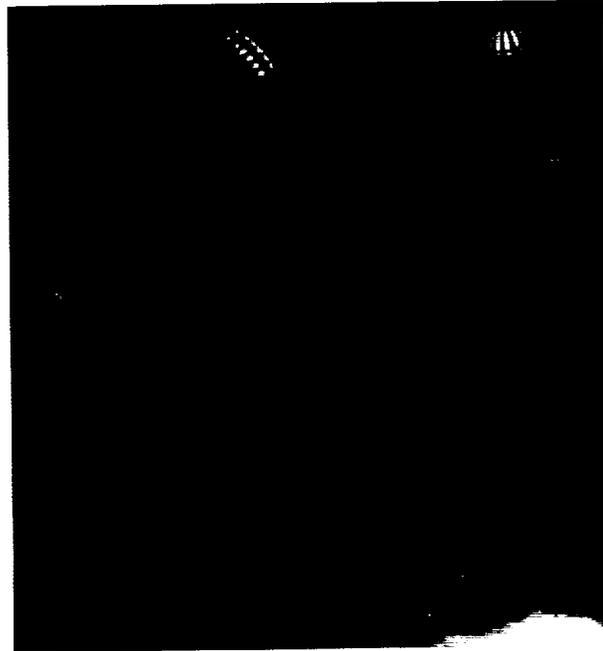
GIANT PLANET DEEP PROBES

SCIENCE OBJECTIVES

- Bulk composition of pre-solar nebula
- Diversity and dynamics of planetary atmospheres
- Global circulation of gas giants

MISSION DESCRIPTION

- Atmosphere probes to Neptune, Saturn, Uranus
- Flight times 5–7 years
- Separate launches using Delta-class vehicles
- Maximum flight system commonality
- Data relay via carrier spacecraft
- Penetration depth for data return limited by available power and telecommunications capability



MEASUREMENT STRATEGY

- Chemical and isotopic composition at depths of 20–100 bars
- Pressure, temperature, winds

TECHNOLOGY STRATEGY

- Miniaturized chemical and isotopic sensors
- Lightweight thermal protection systems
- Efficient solar arrays for outer Solar System applications
- Aerodynamic power generation

Figure 4-5: Roadmap Mission: Giant Planet Deep Probes

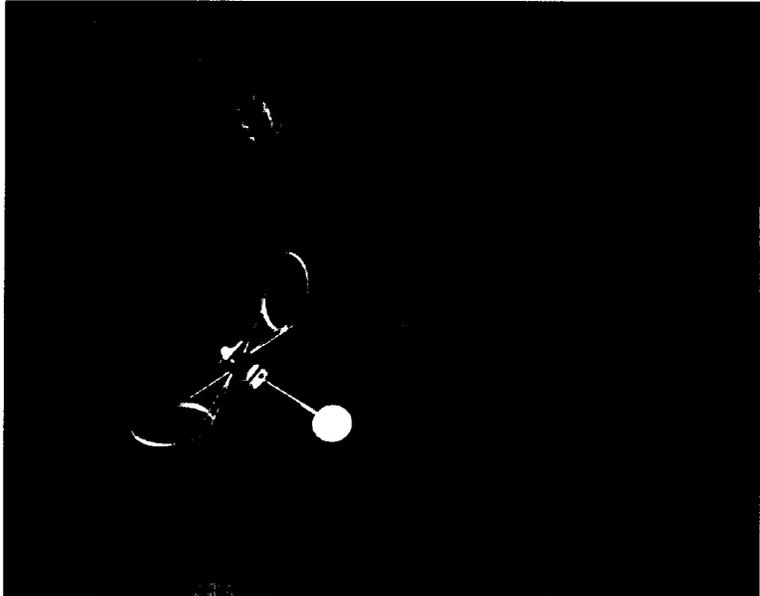
EUROPA OCEAN EXPLORER

SCIENCE OBJECTIVES

- Determine presence of Europa subsurface water
- Measure ice thickness and interior properties
- Image surface features

MISSION DESCRIPTION

- Delta-class launch
- Direct flight to Jupiter in 2.5 yrs
- Europa flybys in one year for observations and orbital energy reduction
- Insertion into Europa orbit for extended observations, depending on propulsion capability



MEASUREMENT STRATEGY

- Radar sounding of ice thickness
- Radiometric tracking for gravity field determination
- Multispectral imaging of global and local features
- Scatterometer studies of surface roughness using radio telecommunications system as a radar

TECHNOLOGY STRATEGY

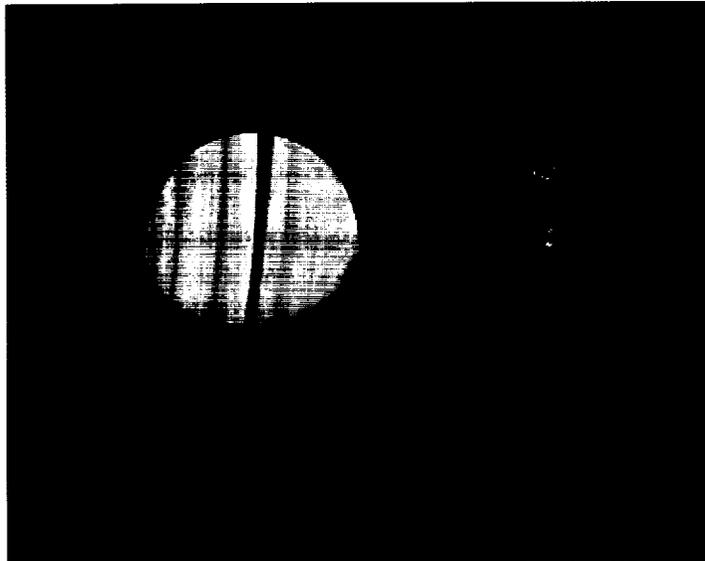
- Low mass propulsion
- Radiation-tolerant components
- Efficient, lightweight solar power generation at Jupiter
- Option: Advanced radioisotopic power generator

Figure 4-6: Roadmap Mission: Europa Ocean Explorer

TITAN ORGANIC EXPLORER

SCIENCE OBJECTIVES

- Distribution and composition of organics
- Organic chemical processes in atmosphere and surface
- Detection of prebiological or protobiological chemistry
- Dynamics and global winds
- Surface morphology



MISSION DESCRIPTION

- Delta-class launch
- Aerobot with vertical mobility for periodic descents to Titan surface
- Longitudinal motion using wind patterns
- Titan orbiter for science and data relay
- Possible data relay via Cassini Extended Mission

MEASUREMENT STRATEGY

- *In situ* measurements of organics in atmosphere and surface
- Cloud chemistry and methane abundance
- Infrared/visible imaging using atmospheric spectral “windows”
- Altimetry of surface topography

TECHNOLOGY STRATEGY

- Aerobot navigation, communication, and autonomous control
- Low temperature balloon envelopes
- Miniature *in situ* chemistry lab
- Aerocapture at Saturn and/or Titan
- Advanced radioisotope generator

Figure 4-7: Roadmap Mission: Titan Organic Explorer

EUROPA LANDERS

SCIENCE OBJECTIVES

- Measure ice thickness and tomography of layers
- Analyze chemistry of surface ice and organics
- Determine interior structure



MISSION DESCRIPTION

- Delta-class Launch of 3 landers and support/delivery vehicle
- Landers and/or penetrators carry miniature geophysics/chemistry labs
- Ice penetration for radiation protection and improved seismic sensitivity
- Data relay via support vehicle in Europa or Jupiter orbit

MEASUREMENT STRATEGY

- Study natural or induced seismic vibrations
- Analyze organics on surface using gas chromatography
- Study heat flow and other physical properties

TECHNOLOGY STRATEGY

- High performance, low mass propulsion
- Radiation-tolerant components
- Airless-body lander system
- Miniature *in situ* laboratories for geophysics and chemistry
- Power for small landers: Solar blankets or radioisotope system

Figure 4-8: Roadmap Mission: Europa Landers

LUNAR GIANT BASIN SAMPLE RETURN

SCIENCE OBJECTIVES

- Mantle composition and age
- Planetary accretion near Earth
- Dynamics of very large impacts

MISSION DESCRIPTION

- Delta III class launch vehicle (may not be adequate)
- Orbital imaging for site selection prior to landing (target is South Pole-Aitken Basin)
- Mobility provides access to multiple sites
- Direct return to Earth, or docking in lunar orbit
- Alternative: *in situ* sample analysis (if return is too difficult)



MEASUREMENT STRATEGY

- Semiautonomous sample selection using orbiter as communication relay
- Multiple 1-kg samples preferred
- Chemical analysis, age dating, microscopy, mineralogy on returned samples

TECHNOLOGY STRATEGY

- Efficient, lightweight propulsion for airless body landing and ascent
- Precision navigation and landing
- Sample acquisition, packaging, and return
- Lander mobility
- Option: Autonomous rendezvous and docking with return vehicle

Figure 4-9: Roadmap Mission: Lunar Giant Basin Sample Return

IO VOLCANIC OBSERVER

SCIENCE OBJECTIVES

- Active volcanism on Io
- Surface/atmosphere interactions
- Differentiation of Galilean satellites
- Interior structure and tidal effects
- Atmospheric composition



MISSION DESCRIPTION

- Delta-class launch vehicle
- 2-year flight to Jupiter
- Galilean satellite gravity assists to reduce orbital energy
- 1-year mission in Io orbit

MEASUREMENT STRATEGY

- Visible imaging to observe surface deformations and volcanic eruptions
- Thermal imaging to study volcanic evolution on Io
- High resolution ultraviolet spectroscopy to measure atmospheric processes
- Radio tracking to measure gravity fields

TECHNOLOGY STRATEGY

- Radiation-tolerant electronics
- Autonomous feature detection and tracking
- Ultra lightweight spacecraft and payload
- Temperature-insensitive electronics
- Efficient, radiation-tolerant solar arrays
- Efficient, lightweight chemical propulsion

Figure 4-10: Roadmap Mission: Io Volcanic Observer

MARS SURFACE NETWORK

SCIENCE OBJECTIVES

- Mars seismicity and interior structure
- Local magnetism
- Atmospheric circulation
- Surface/subsurface thermal properties

MISSION DESCRIPTION

- Med-lite launch vehicle
- Ballistic trajectory and direct entry at Mars
- Four or more Mars surface stations and/or penetrators
- Lifetime of 1 Martian year
- Data relay via Mars orbiter



MEASUREMENT STRATEGY

- Precision seismometry at 4 sites
- Pressure and temperature of the atmosphere
- Wind measurement
- Magnetometer deployment
- Subsurface heat flow

TECHNOLOGY STRATEGY

- Microlanders and/or penetrators
- Miniature geophysics stations
- Power for small vehicles
- Ambient temperature electronics

Figure 4-11: Roadmap Mission: Mars Surface Network

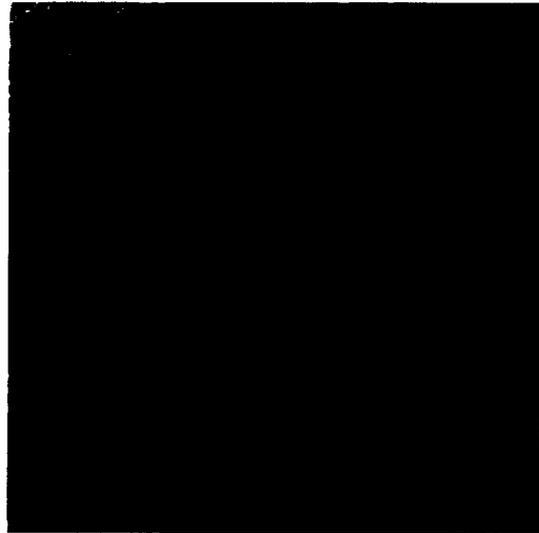
VENUS SURFACE MISSION: LANDERS AND AEROBOTS

SCIENCE OBJECTIVES

- Interior structure, volcanism, and tectonics
- Composition and dynamics of lower atmosphere
- Interaction of atmosphere with surface
- Detailed surface morphology

MISSION DESCRIPTION

- Delta III launch
- 100-kg aerobot
- Oscillate in and out of clouds (40–60 km)
- Brief excursions to surface
- Vertical buoyancy control via “reversible fluid” system
- Mobility using zonal wind patterns
- Relay data via orbiter



Venusian surface as seen by Venera Lander

MEASUREMENT STRATEGY

- Temperature, pressure, and chemical analysis of the atmosphere
- Elemental and mineralogical analysis of surface
- Radio tracking for atmosphere circulation measurements
- Seismometry
- Magnetometer deployment
- High-resolution imaging

TECHNOLOGY STRATEGY

- Active cooling and/or high-temperature electronics
- Efficient thermal-to-electric conversion
- Lightweight instrument and delivery system
- Aerobot materials and control systems
- Miniature geophysics stations

Figure 4-12: Roadmap Mission: Venus Surface Mission

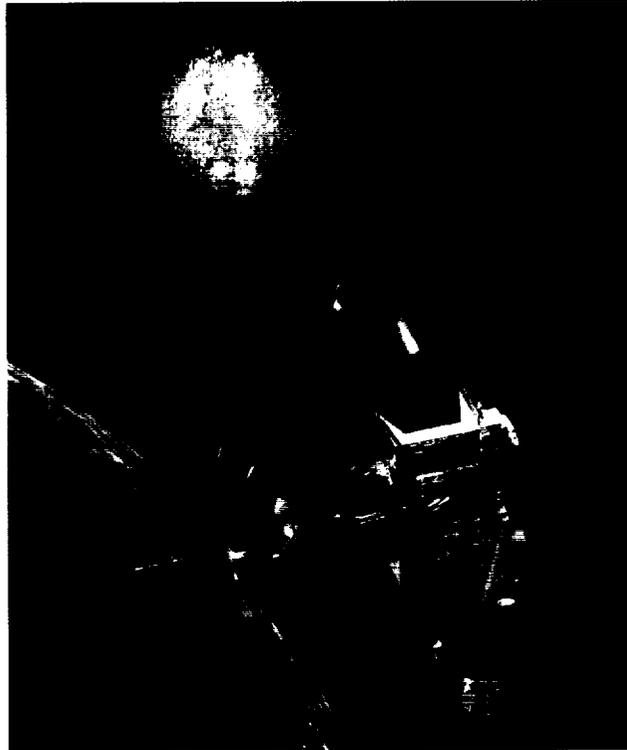
MERCURY ORBITER

SCIENCE OBJECTIVES

- Surface and atmosphere composition
- Magnetic field generation
- Evidence of volcanic and tectonic activity and mantle dynamics
- Planetary accretion near Sun
- Global early cratering history

MISSION DESCRIPTION

- Delta II launch vehicle
- 3-year flight with Venus and Mercury gravity assists (conventional propulsion)
- One year mission (1st global map in 120 days)
- Elliptical, polar orbit simplifies thermal control
- Possible joint mission with Sun-Earth Connection



MEASUREMENT STRATEGY

- Multispectral map of surface geology
- Magnetic and gravity field measurements
- Ultraviolet measurements of atmosphere composition
- Light detection and ranging (Lidar) altimetry

TECHNOLOGY STRATEGY

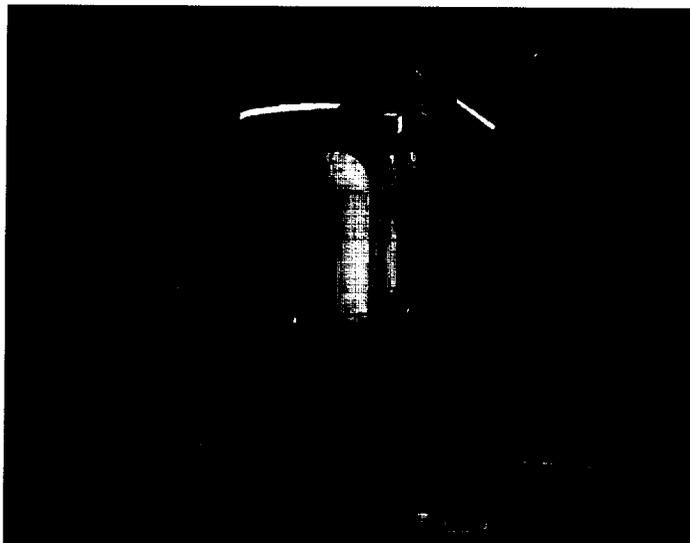
- Thermal control and survivability
- SEP or solar sail propulsion to reduce flight time
- Robust solar power system

Figure 4-13: Roadmap Mission: Mercury Orbiter

FIRST MARS SAMPLE RETURN

SCIENCE OBJECTIVES

- Mineralogical and elemental analyses of soil and possibly rock
- Isotopic dating of first samples returned from Mars
- Investigate atmospheric evolution and mechanisms of escape
- Demonstrate systems for future Mars Sample Return missions



MISSION DESCRIPTION

- Return samples of soil and atmosphere, and possibly rock, for analysis in Earth laboratories
- Sample mass approximately 0.5 kg
- Direct entry at Mars; propulsive descent to soft landing
- Surface stay time several hours to several days
- Sample return capsule, direct entry at Earth

MEASUREMENT STRATEGY

- Short-range rover may be used for sample selection; simple “grab sample” as back-up
- Sample analyses in Earth laboratories

TECHNOLOGY STRATEGY

- High-impulse ascent propulsion system
- Highly integrated lander/ascent vehicles
- Autonomous, sterile sample collection
- Sample packaging and preservation

Figure 4-14: Roadmap Mission: First Mars Sample Return

MARS WATER AND MINERALOGY MAPPER

SCIENCE OBJECTIVES

- Find highest concentrations of water in the top meter of the Martian surface (resource mapping)
- Locate sites of aqueous sedimentation (mineral mapping)
- Search for environments conducive to past or present life (e.g., lake bed deposits, geothermal vents)
- Help identify high-priority sites for sample return missions

MISSION DESCRIPTION

- Med-lite launch vehicle
- Orbit insertion via aerocapture
- Polar orbit (Sun-synchronous)
- Communication relay for surveyor landers
- 5-year mission duration

MEASUREMENT STRATEGY

- Map global abundance of water in surface using gamma ray/neutron spectrometer
- Mineralogy: High-resolution mapping spectrometer (100 m)

TECHNOLOGY STRATEGY

- Aerocapture
- Small, lightweight remote sensing instruments

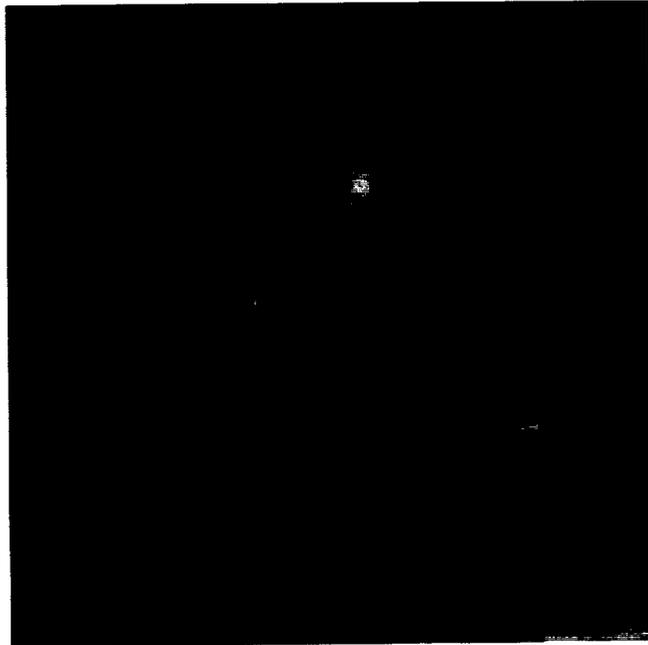


Figure 4-15: Roadmap Mission: Mars Water and Mineralogy Mapper

MARS MOBILE SCIENCE LABORATORIES

SCIENCE OBJECTIVES

- Regional geochemistry and geology
- Detailed investigation of high-priority exobiology sites
- Site selection for sample return missions

MISSION DESCRIPTION

- Direct entry to Mars, propulsive descent
- One Mars year operation, 1–10 km rover range
- Possible sample caching for later pick-up
- Semi-autonomous traverse navigation and planning
- Communications via relay orbiter



MEASUREMENT STRATEGY

- Visible and infrared imaging and spectroscopy
- Mass spectrometry
- Rock chipping to remove weathering rind
- Possible microscopy of rock and soil samples

TECHNOLOGY STRATEGY

- Survivability at low temperatures
- Power for long-duration roving
- Autonomous, long-range roving
- Miniature chemistry and mineralogy instruments
- Rock/soil-coring devices
- Sample selection methodology
- Advanced communications for lower mass, higher data rates, and lower power consumption

Figure 4-16: Roadmap Mission: Mars Mobile Science Laboratories

MARS GEOSCIENCE AEROBOTS

SCIENCE OBJECTIVES

- High-resolution mineralogy and geochemistry
- Location of optimum sites for exobiologic sample return
- Acquisition of data for resource objectives (rock-size distributions, water mapping at km scales)



MISSION DESCRIPTION

- One or more aerobots at 4–6 km altitude
- Deployment of aerobot(s) to provide coverage over maximum terrain diversity
- Operation of more than 50 days
- Relay through communications orbiter

MEASUREMENT STRATEGY

- Surface mineralogy at 100 m for representative terrains
- Sub-meter surface morphology
- *In situ* atmospheric temperature, pressure, and circulation

TECHNOLOGY STRATEGY

- Telerobotics
- Aerobot deployment
- Lightweight instruments
- Thermal control
- Super-pressure balloon envelope materials
- Power generation
- Relay communications

Figure 4-17: Roadmap Mission: Mars Geoscience Aerobots

ADVANCED MARS SAMPLE COLLECTION AND RETURN

SCIENCE OBJECTIVES

- Chronology of Mars surface
- Search for evidence of past or present life
- Climate and volatile history

MISSION DESCRIPTION

- Return diverse set of samples (rocks, soil, and atmosphere) for analysis in Earth laboratories
- Precision landing to selected site, including previous caches
- Rover for access to variety of samples, including previous caches
- Possible rendezvous and sample transfer in Mars orbit
- Sample return capsule direct entry to Earth



MEASUREMENT STRATEGY

- Mineralogy for sample selection (geochemical analysis, IR spectroscopy, visible imaging, and microscopy)
- Sample analyses in Earth laboratories

TECHNOLOGY STRATEGY

- Demonstrated descent and ascent capability
- Sample selection and collection systems
- *In-situ* mineralogy and chemistry, arms, drills, corers, rover
- Sample packaging and preservation to meet planetary protection requirements
- Precision landing
- Power
- Communication relay

Figure 4-18: Roadmap Mission: Advanced Mars Sample Collection and Return

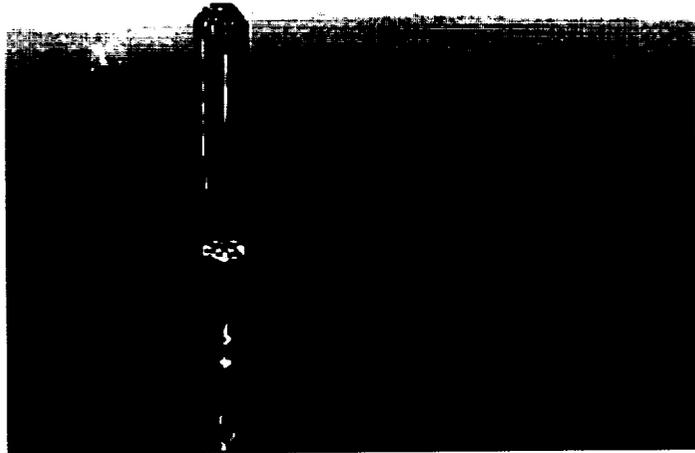
VENUS GEOSCIENCE AEROBOTS

SCIENCE OBJECTIVES

- Surface mineralogy and geochemistry
- Composition and dynamics of lower atmosphere
- Interactions with surface
- Outgassing to exosphere

MISSION DESCRIPTION

- Med-lite launch
- Two aerobots (100 kg each)
- Nominally in middle atmosphere
- Brief excursion down to surface (perhaps to mountain top)
- Vertical buoyancy control via “reversible fluid” system
- Mobility using zonal wind patterns



MEASUREMENT STRATEGY

- Visual/infrared (IR) measurements from aloft
- Temperature, pressure, and chemical atmospheric analyses
- Mineralogical analysis of surfaces
- Radio tracking for circulation and occultation measurements

TECHNOLOGY STRATEGY

- Telerobotics
- Autonomous state determination and navigation
- Thermal control
- High-temperature balloon envelopes
- Power generation
- Lightweight science instruments
- Relay communications

Figure 4-19: Roadmap Mission: Venus Geoscience Aerobots

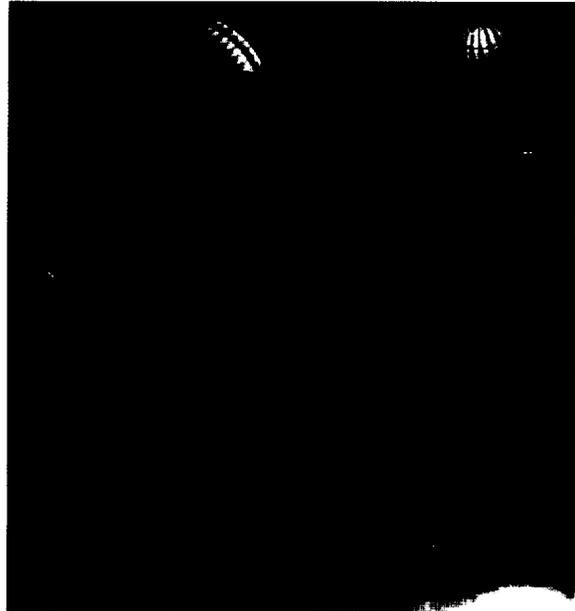
OUTER PLANET MULTIPROBES

SCIENCE OBJECTIVES

- Understand the diversity of outer planet atmospheres
- Structure, dynamics, and global circulation of gas giant atmospheres

MISSION DESCRIPTION

- Multiple atmospheric probes to Neptune, Saturn, Jupiter, Uranus (priority order)
- Launch vehicle: Delta II (Saturn, Jupiter, Uranus) or Delta III (Neptune)
- Flight times 5–7 years
- Coordinated entry sites and times
- Data relay via carrier spacecraft



MEASUREMENT STRATEGY

- Pressure, temperature, winds, thermal balance, sound speed, solar flux
- Chemical and isotopic abundances via mass spectrometry
- Multiple entry sites; spatial and temporal variations

TECHNOLOGY STRATEGY

- Miniaturized chemical and isotopic sensors
- Lightweight thermal and pressure protection systems
- Efficient power for outer Solar System applications
- Multiprobe deployment
- Relay communications
- Efficient transportation to outer Solar System

Figure 4-20: Roadmap Mission: Outer Planet Multiprobes

JUPITER POLAR ORBITER

SCIENCE OBJECTIVES

- Interior structure
- Atmospheric circulation at all latitudes
- Magnetosphere structure and dynamics
- Auroral phenomena

MISSION DESCRIPTION

- Delta-class launch vehicle
- 2.5 year direct flight to Jupiter
- Delivered mass roughly 250 kg
- 1–2 years in high-inclination Jupiter orbit



MEASUREMENT STRATEGY

- Magnetometer
- Charged particle detectors
- Radio/plasma wave detectors
- Multi-spectral imaging (infrared visible, ultraviolet)
- Radio science and occultations

TECHNOLOGY STRATEGY

- High-performance chemical propulsion
- Radiation-tolerant components
- Efficient, low-mass solar power generation at Jupiter distance
- Wide dynamic range magnetometer

Figure 4-21: Roadmap Mission: Jupiter Polar Orbiter

NEPTUNE ORBITER WITH TRITON FLYBYS

SCIENCE OBJECTIVES

- Atmospheric structure and circulation at Neptune and Triton
- Ring particle physical properties, dynamics, and distribution
- Magnetosphere structure and dynamics
- Map the gravity field (Neptune)
- Composition, structure, and activity of Triton surface

MISSION DESCRIPTION

- Delta-class launch vehicle
- Flight time: 6–7 years using advanced solar electric propulsion (SEP)
- Autonomous operation and navigation
- Aerocapture for orbit insertion
- Daily flybys of Triton possible

MEASUREMENT STRATEGY

- Multispectral imaging (UV/visible/near IR)
- Mid-IR spectrometry or radiometry
- Magnetometer
- Radio science

TECHNOLOGY STRATEGY

- High power SEP with large (10-m) inflatable solar collectors
- Aerocapture
- Autonomous spacecraft operations
- Temperature-tolerant electronics (50 K at Neptune)
- Lightweight spacecraft systems
- Advanced telecommunications: Optical or large-diameter inflatable antenna



Figure 4-22: Roadmap Mission: Neptune Orbiter with Triton Flybys

SATURN RING OBSERVER

SCIENCE OBJECTIVES

- Understand ring processes and evolution as a model for the origin of planetary systems
- Ring particle physical properties, dynamics, and spatial distribution
- Composition of ring particles



MISSION DESCRIPTION

- Roughly 100 kg spacecraft
- Delta-class launch vehicle
- 3–5 year flight to Saturn
- Low-inclination Saturn orbit with ring-plane crossings through ring division(s)
- Propulsion required to maintain safe orbit

MEASUREMENT/STRATEGY

- Multispectral imaging, spectrometry, and radiometry
- Dust particle analysis including mass spectroscopy
- Fields and plasma detectors

TECHNOLOGY STRATEGY

- Advanced propulsion: chemical or SEP
- Solar concentrators and/or very high efficiency solar arrays or high efficiency radioisotope power sources
- Ultra-lightweight spacecraft
- Autonomous navigation through rings
- Particle impact shielding

Figure 4-23: Roadmap Mission: Saturn Ring Observer

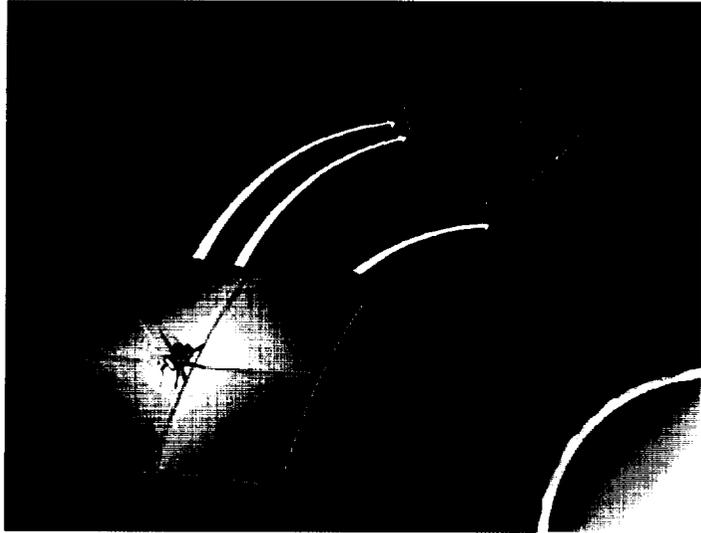
MERCURY MAGNETOSPHERIC MULTI-SATS

SCIENCE OBJECTIVES

- Magnetosphere structure and dynamics
- Evolution of surface material
- Composition, structure, and dynamics of the atmosphere

MISSION DESCRIPTION

- Delta or med-lite launch vehicle
- Solar sail preferred; enables 50% flight time reduction
- Mother plus one or two daughter spacecraft: terminator, equatorial, and L_1 orbits
- Total mass on orbit: 400 kg
- 1-year mission at Mercury



MEASUREMENT STRATEGY

- Magnetic field studies
- Plasmas/fields/waves upstream and in magnetosphere
- Ultraviolet observations of atmosphere/aurorae
- Imaging and radio science

TECHNOLOGY STRATEGY

- Solar sail or advanced SEP
- Thermal control and survivability
- Lightweight spacecraft systems
- Lightweight, integrated instruments

Figure 4-24: Roadmap Mission: Mercury Magnetospheric Multi-Sats

CHAPTER 5

ROADMAP TECHNOLOGY

REQUIREMENTS

As the Solar System exploration program progresses, ever more challenging missions will be required to advance the “state of the science” and provide answers to the next generation of scientific questions. Whereas the early decades of Solar System exploration were dominated by conceptually simple flybys and planetary orbiters (exceptions were Pioneer Venus and Viking), many of the future missions identified in the roadmap require extended encounters within the atmospheres or on the surfaces of planetary bodies, moving around within these environments, acquiring and analyzing samples, and even returning them to Earth. Future missions will also require survival in harsh thermal or radiation environments that were not targets during the early years of the program. Paradoxically, these fundamentally more challenging missions must be undertaken with budgets that are severely constrained and are frequently capped at the initiation of a project, leaving little room for cost growth as the mission development proceeds.

Nonetheless, within this environment of challenging missions and limited budgets, a robust and exciting planetary program can exist. The key to such a program is a sound portfolio of investments in new technologies and a measured approach to their infusion into science missions. Many of these new technologies will simply enable well-understood objectives to be met at affordable costs, while other developments represent fundamentally new capabilities, without which a given mission would be impossible at any cost. In either case, technology needs must be identified well in advance of their intended application, and they must be thoroughly tested in the lab, and possibly in space, prior to their use on a science mission.

CAPABILITY CATEGORIES

Six “capabilities” summarize the key technology needs for the future planetary programs.

1. Transportation and Mobility
2. Sample Acquisition and Return

-
3. Science Instruments
 4. Power
 5. Communications
 6. Operability

Within each capability category are individual technology developments that will allow the Roadmap missions to be undertaken at reasonable cost. This list of technologies is not exhaustive in that each one may comprise several independent developments in a variety of disciplines. In addition, different technological solutions may exist for any given problem, so the specific technology development pathway that leads to a given mission depends on further analysis.

5.1 TRANSPORTATION AND MOBILITY

Transportation and Mobility is the capability to travel to a planetary destination, enter orbit or descend to the surface upon arrival, move about on the surface or within the atmosphere, and ascend from the surface for sample return missions. Given the spectrum of challenging missions in this Roadmap, a variety of individual technologies is required to provide this capability. These are listed in Table 5-1.

Table 5.1: Technologies required for transportation and mobility

<p>Ultra-high efficiency interplanetary propulsion Advanced solar electric propulsion Solar sail</p>
<p>Aerocapture Mars and outer planets</p>
<p>Aerobots Venus, Mars, Titan</p>
<p>Ascent and descent systems High specific impulse (I_{sp}), low-mass chemical propulsion Airless-body lander system</p>
<p>Advanced roving vehicles Mars "mobile science lab" Small, scalable rovers</p>
<p><i>In situ</i> resource utilization (propellant factories)</p>

5.2 SAMPLE ACQUISITION AND RETURN

The Sample Acquisition and Return capability requires technologies to acquire and return samples from a) comets and asteroids, and b) planets and satellites. These bodies present a wide range of physical conditions under which the various mechanisms must work. At present, many physical parameters on the surfaces of asteroids and comets are unknown. Temperatures that may be encountered for sample acquisition and return technologies range from tens of kelvins to 600 K or more. Gravity conditions range from the micro-g levels upwards. Drilling may be through ice and rock. Sample acquisition and return technologies are listed in Table 5-2.

Table 5-2: Technologies required for sample acquisition and return

<p>Sampling of comets and asteroids Coring penetrator with tether Landing and anchoring on low-gravity bodies Collection of surface rocks and dust Drilling to obtain subsurface cores Intact capture of gas and dust</p> <p>Sampling of planets and satellites Collection of rocks and soil Fragmentation and chipping of rocks Drilling/coring to access subsurface soil and ices Atmosphere sample acquisition</p> <p>Sample handling and return Aseptic sample transfer Preservation of volatiles Lightweight return capsule</p>

5.3 SCIENCE INSTRUMENTS

Many new instruments and improvements in instruments will be needed to accomplish the Roadmap activities. All instruments must be made smaller and lighter in the future. New instruments will be needed to provide age-dating measurements and *in situ* chemical analysis of samples. Durability will be required for landing and takeoff maneuvers, and during measurement intervals in hostile environments. For long duration missions, radiation-hardened electronics must be improved. Science instrument technologies are listed in Table 5-3.

Table 5-3: Technologies required for science instruments

<p>Advanced detectors for all types of missions Instrument focal planes: Infrared, mm and sub-mm, gamma-ray Organic chemistry sensors for landers and probes Seismometers and meteorology sensors</p> <p>Miniature surface laboratories for geophysics, geochemistry, and biochemistry</p> <p>Lightweight integrated remote-sensing instruments</p> <p>Improved survivability of detectors and instruments Tolerant of radiation, pressure, temperature extremes</p>
--

5.4 POWER

The Roadmap missions will impose many new requirements on power generation and storage systems (Table 5-4). The new generation of power systems must be able to operate at both high- and low-temperature extremes. They must survive in harsh radiation environments for long periods of time. They must be robust and efficient.

Table 5-4: Technologies required for power

<p>Advanced power generation Improved solar arrays: Robust, tolerant of temperature and radiation, useful at outer planets Solar reflectors and concentrators Improved radioisotope power sources: Low-mass, efficient, robust</p> <p>Power for small vehicles Low-power, long-life sources Solar and non-solar Impact tolerant for use on landers, rovers, seismic/meteorology stations</p> <p>Advanced, efficient rechargeable batteries Tolerant of temperature extremes</p>
--

5.5 COMMUNICATIONS

Communications systems (Table 5-5) including Earth-based, spacecraft, and lander/rovers will need to be improved to meet the communication requirements for the Roadmap missions.

Table 5-5: Technologies required for communications

<p>Improved, low-mass telecom components for all missions Small deep-space transponder “Tiny transponder” Microelectronics and miniaturization</p> <p>New deep-space telecom capabilities for far-term missions Large inflatable antennas Optical communications Ka-band and optical Earth-receive stations</p> <p><i>In Situ</i> communications technologies for landers/rovers Phased arrays for surface-orbiter link Small optical terminals Network links for inter-station communications</p> <p>Improved Deep Space Network station performance Improved decoder technologies (software/hardware)</p>

5.6 OPERABILITY

A number of improvements in the operability of spacecraft will be required to complete the Roadmap missions. Spacecraft systems will need to operate in extremes of temperature for longer periods of time than previous missions. Autonomous navigation will be required for rendezvous and for landing on comets and asteroids.

Table 5-6: Technologies required for operability

<p>Survivable systems Tolerance to radiation, thermal extremes, impact Long-life systems for outer planet missions</p> <p>Smarter spacecraft: Autonomous, self-sufficient machines Autonomous navigation: Near small bodies During interplanetary cruise and in planetary orbit Precision landing for sample return and <i>in situ</i> exploration Autonomous pointing and feature tracking</p> <p>Information systems On-board: Data editing and selective downlink, predictive modeling for sequence updates On-ground: Data visualization, virtual reality, advanced design techniques</p>
--

5.7 LEADING TECHNOLOGIES AND THEIR RELATIONSHIPS TO THE CAMPAIGNS

From the set of 50 individual technology developments discussed above, 16 were identified as being the most crucial to achievement of the objectives of the five Campaigns. This set has been termed the "Leading Technologies." Table 5-7 summarizes the leading technologies, and Table 5-8 shows the relationships of those leading technologies to the individual Campaigns.

Table 5-7: Most crucial technologies for achieving the five Campaign objectives

Leading Technology	Requirements Summary	Enables
Smaller Spacecraft	Aggressive mass reduction; focus on microelectronics, innovative architectures	Minimal launch vehicle, flight time, and cost
Smarter Spacecraft	Enhanced S/C autonomy; autonomous navigation, fault detection, data handling	Minimal OPS costs, reduced risk for long-duration missions
Advanced Detectors	Improved spectral range, on-chip integration, multi-spectral focal planes	Improved sensitivity, science return at minimal cost
Information Systems	Advanced data visualization and modeling; new S/C design tools; high-performance computing	Improved data access for scientists and public
Small-Body Sampling Systems	Sample surface/subsurface at comets and asteroids; selection, packaging, preservation	Return of pristine samples to Earth
Advanced Power Generation	Improved efficiency, robust radioisotope generators; improved solar arrays	Outer Solar System missions using low-mass S/C
Ultra-high Efficiency Interplanetary Propulsion	Advanced solar-electric propulsion, solar sail	High-energy missions on small launch vehicles
Survivable Systems	S/C systems tolerant of thermal extremes, radiation, impact, pressure	<i>In situ</i> exploration of harsh environments; minimal S/C mass
Miniature Geophysics Stations	Self-contained lab integrating seismology, meteorology	Low-mass planetary surface missions
Power for Small Vehicles and Spacecraft	Small photovoltaic blankets; small radioisotope sources; efficient secondary batteries	Low-mass, long-lived surface missions and rovers
Miniature Geochemistry Laboratory	Small labs integrating organic and inorganic chemistry sensors, age dating	<i>In situ</i> analysis of samples; intelligent selection for return
Advanced Rovers	Small scalable rovers, 1-km range; long-range rovers up to 10 km	Mars field geology and sample return
Aerobots	Controllable, semi-autonomous balloon systems	<i>In situ</i> exploration of atmospheres and surfaces of Venus, Mars, Titan
Mars Communications "Trunk Line"	Communications infrastructure to support extended Mars exploration program	High-bandwidth, coordinated data return from multiple vehicles
Ascent and Descent Systems	Sample return vehicles; high I_{sp} chemical propulsion or <i>in situ</i> propellant production	Mars sample return missions
Aerocapture	Systems and software for aerocapture at Mars and outer planets	Minimum cost and flight time for Mars and outer-planet missions

Table 5-8: Connections between the leading technologies and Campaigns, indicating which technologies are important and which are critical.

Campaign	Leading Technology															
	Aerobots	Aerocapture	Ascent/Descent Systems	Detectors-Advanced	Geochemistry Lab	Geophysics Lab	Information Systems	Power Generation	Power-small vehicles	Propulsion-Interplanetary	Rovers-Advanced	Sampling-Small Bodies	Smaller Spacecraft	Smarter Spacecraft	Survivable Systems	Trunk Line - Mars
Building Blocks			•	√	•		√	√	•	√		√	√	√	•	
Prebiotic Chemistry	•	•	•	√	•	•	√	√	•				√	√	•	
Formation/Dynamics	•		•	√		√	√	•	•		•		√	√	√	
Earth-Like Environments	√	•	√	√	√	•	√		√		√		√	√	•	√
Astrophysical Analogs		√		√			√	√		√			√	√	√	

√ Critical to this campaign

• Important to this campaign

CHAPTER 6

OUTREACH AND PUBLIC PARTICIPATION

As part of its effort to have this Roadmap document represent and be understood by the general public (as well as scientific and technological interest groups), the Roadmap Development Team wrote a separate description of Quests and Campaigns in common language so that they could be easily understood by the general public. Public involvement from the beginning encourages the public to understand the risks and rewards, to share the emotions of success and failure, and to feel the excitement of the first new discoveries. The three Quests and five Campaigns discussed in Chapters 2 and 3 were reframed as follows:

Quest 1: Looking Back

This Quest deals with understanding the formation and evolution of our Solar System and of our Earth. Typical questions raised by this Quest are:

- How did the Earth and the other planets form?
- Why is the Solar System so diverse and the Earth so unique in the Solar System?
- What can we learn about the Earth by studying the Solar System as a natural science laboratory?

Quest 2: Looking Ahead

This Quest deals with the future of humankind. Typical questions raised by this Quest are:

- How does the Solar System affect the future habitability of Earth?
- What resources beyond Earth might be of interest to humankind?
- Which space environments might be suitable for human exploration?

Quest 3: Looking Outward

This Quest deals with seeking the origins of life and its possible existence elsewhere in the Solar System and in the Universe. Typical questions raised by this Quest are:

- What can we learn about the building blocks of life by understanding the history and presence of water and life-building molecules in other Solar System bodies?
- What conditions are required for the emergence of life?
- What evidence exists of past and present life elsewhere in our Solar System?

Campaign: Building Blocks and Our Chemical Origins

What are the conditions necessary for life to develop? The answer may lie in understanding how the planets formed in the early Solar System out of a primordial cloud of gas and dust (solar nebula). Even today, billions of years after the planets coalesced, primitive bodies such as asteroids and comets may contain a record of these early processes. Similarly, deep within the interiors of the gas giant planets may lie clues to understanding what conditions were like in the early Solar System.

In these primitive bodies, NASA will seek the origins of organic (life-forming) materials, precursors to life, and how they may have come to be part of the newly formed Earth. Surveying these planetary bodies, large and small, should also yield an inventory of accessible resources beyond Earth that may be useful in the future Solar System exploration.

Possible missions to support this campaign include:

- The Pluto/Kuiper Express: two small spacecraft to fly by Pluto and its moon, Charon, to study their surfaces, and to fly by a smaller Kuiper Belt object
- Champollion to land on a comet to analyze its surface and possibly return a sample to Earth
- Outer Planet Probes to study the deep atmospheres of Neptune, Saturn, and Jupiter
- Small-body Visitors to fly by a variety of asteroids and comets to study their compositions
- Small Body Sample Returns to retrieve material from a near-Earth asteroid and eventually from the surface of a comet

Campaign: Prebiotic Chemistry in the Outer Solar System

Some planetary bodies are excellent biological laboratories that might yield clues as to how planetary evolution can lead to life. Europa and Titan are good examples. Europa is a Moon-sized body covered by a smooth layer of water ice. Oceans of liquid water may exist under this ice covering. Because liquid water is a requirement for life as we know it, Europa is a promising object to study. Could Europa's internal heating produce hydrothermal (superheated water) vents similar to those found in Earth's oceans? If so, could these ocean vents on Europa, like those on Earth, harbor life forms that do not need sunlight?

Titan, by contrast, has a thick atmosphere and an organic chemistry powered by sunlight. Could Titan contain organic materials needed for life to emerge?

Possible missions that support this campaign include:

- An Ocean Explorer to search for liquid water beneath Europa's icy surface
- The Lander Network to analyze and penetrate Europa's icy surface
- An Organic Explorer to be a balloon-borne laboratory studying organic molecules, the precursors to life, on Titan.

Campaign: Formation and Dynamics of Earth-Like Planets

Like the Moon and Mercury, the primitive Earth suffered heavy bombardments from space that altered its crust. The earliest planetary history of the Earth has been erased by billions of years of geologic change, but the Moon and Mercury have remain virtually unchanged. They are excellent models for understanding Earth's early history as a planet and how its evolution diverged from that of other planets.

Earth has a dynamic interior manifested by earthquakes and volcanic eruptions. Mercury, Venus, Mars, and Io also show evidence of active interiors. Studying them will offer us several points of comparison to better understand the forces at work in the Earth's interior.

Possible missions that support this campaign include:

- A Volcanic Observer to study Io's active volcanoes
- Seismic Landers to study plate tectonics on Venus
- A Surface Network on Mars to do surface, atmosphere, and interior measurements
- A Sample Return to retrieve lunar mantle material (i.e., rocks from deep below the surface) for study back on Earth

Campaign: Evolution of Earth-Like Environments

Earth, Mars, and Venus have similar origins, yet each has evolved very differently. Mars has the greatest chance for having also developed life because it may have had that crucial ingredient for life, liquid water. Therefore, the search for evidence of liquid water on Mars, be it present or past, will be a prime science objective in this campaign.

On Venus, the runaway greenhouse effect and the possibility that liquid water might once have existed are of special interest because they may offer insights into Earth's future habitability, and the likelihood of habitable planets around other stars.

Possible missions to support this campaign include:

- A Water and Chemistry Mapper to find the highest concentrations of water in the top meter of the Martian surface
- A Mineralogical Mapper to search for environments most conducive to present or past life on Mars
- A Field Geology Rover to track across sites where life forms or fossils are most likely to be present
- Mars Sample Returns to return Martian soil samples to Earth allow a thorough search for signs of life
- Aerobots (balloon-borne robots) to study the atmosphere of Venus

Campaign: Astrophysical Analogs in the Solar System

Our Solar System is a physics laboratory of immense scale. By observing certain phenomena, we can better understand how the Solar System formed and what scientific principles connect systems of such radically different size, from laboratory to cosmic scales.

This Campaign will study a diverse collection of objects: comets, magnetospheres, and atmospheres of different planets and ring systems.

Possible missions to support this campaign include:

- Saturn Ring Observer to understand the physical properties of the rings, as well as their evolution
- Neptune Orbiter with Triton Flybys to understand planetary atmospheres, rings, and magnetic fields

-
- Magnetospheric Explorer to understand Mercury's magnetic field and to investigate the planet's evolution
 - Polar Orbiter to Jupiter to investigate the gas giant's interior and understand its atmosphere, magnetic field, and magnetosphere

APPENDIX A

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• Ball Aerospace and Technologies	Spacecraft technology, public outreach
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• Honeybee Robotics	Robotic and sampling technology
• International Space Enterprises	Public Participation, Education
• iN SITE	Public Communication
• Irvine Sensors	Advanced electronics technology
• L'Garde, Inc.	Inflatable and lightweight structures
• Lockheed Martin Astronautics	Spacecraft technology
• Olin Aerospace	Advanced propulsion technology
• Rockwell International	Spacecraft technology and public outreach
• Southwest Research Institute	Composite structures technology
• SSG, Inc.	Spacecraft technology
• TRW	

APPENDIX B

**U. S. LUNAR AND PLANETARY
MISSIONS THROUGH 1997**

NASA PLANETARY SPACE MISSIONS: AN OVERVIEW

- A series of Mariner, Ranger, Surveyor, and Pioneer spacecraft in the 1960s and 1970s began humankind's initial reconnaissance of the Solar System. The Pioneer 10 and 11 spacecraft are currently in the Kuiper belt, poised to leave the Solar System.
- Two Viking spacecraft, each divided into a lander and an orbiter, explored Mars in the 1970s. Viking Lander 1 became the first spacecraft from Earth to land on the Red Planet. Findings were inconclusive but tantalizing. For instance, the water erosion features led to questions of what happened to the water and did life begin where liquid water was present on Mars?
- The twin Voyager spacecraft studied the four largest planets in the Solar System. Their planetary mission began at Jupiter in 1979 and concluded with Neptune 10 years later. In their journeys, the Voyager spacecraft investigated 4 planets, 50 moons, and the interplanetary medium of the Solar System.
- The Magellan spacecraft mapped 98% of Venus, discovered active geology, and performed the first aerobraking maneuver, pioneering a technique that is now in use in the Mars exploration program.
- The Galileo spacecraft sent back important new information on its mission to Jupiter. It provided intriguing circumstantial evidence for a liquid water ocean beneath the crust of Europa. It discovered around the satellite Ganymede, the first "magnetosphere" of a planetary satellite within the Jovian magnetosphere. It passed through the most intense interplanetary dust storm ever measured, and it was able to observe the collision of Comet Shoemaker-Levy 9 with Jupiter.

A listing of U. S. Lunar and Planetary missions through 1997 follows. Additional information including references to former U.S.S.R., European, and Japanese missions can be found on the following two web sites:

http://nssdc.gsfc.nasa.gov/planetary/planetary_home.html
<http://msl.jpl.nasa.gov/home.html>

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
<i>Mariner II</i>	Aug. 27, 1962	Venus	Planetary exploration: first successful interplanetary probe. Found no magnetic field; high surface temperatures of approximately 800°F (430°C). Passed Venus Dec. 14, 1962, at 21,600 miles (34,800 km), 109 days after launch.
<i>Ranger VII</i>	July 28, 1964	Moon	Lunar exploration (photography): Camera system yielded 4,300 high resolution TV pictures with about 2,000 times better definition than present Earth-based photography; objects less than three feet (1 m) in diameter discernible. Impacted July 31, 1964, 68 hours, 36 minutes after launch in Sea of Clouds region, 8–10 miles (13–16 m) from aim point.
<i>Mariner IV</i>	Nov. 28, 1964	Mars	Planetary and interplanetary exploration: Encounter occurred July 14, 1965, with closest approach 6,100 miles (9,800 km). Twenty-two pictures taken.
<i>Ranger VIII</i>	Feb. 17, 1965	Moon	Lunar photography: 7,100 pictures obtained; impact occurred Feb. 20, 1965, about 15 miles (24 km) from target in Sea of Tranquility. Total flight time to impact: 64 hours, 53 minutes.
<i>Ranger IX</i>	Mar. 21, 1965	Moon	Lunar photography: 5,800 pictures obtained; impact less than three miles from target in eastern floor of crater Alphonsus. Pictures converted for "live" viewing on commercial TV. Final mission of <i>Ranger</i> series. Total flight time to impact on Mar. 24, 1965, 64 hours, 31 minutes.
<i>Surveyor I</i>	May 30, 1966	Moon	Lunar exploration: Achieved soft lunar landing on first engineering test flight (with closed loop guidance) at 02:17 EDT June 2, 1966, at 2.41°S, 43.43°W (Ocean of Storms). Data obtained on morphology and lunar origin; bearing strength of <i>Surveyor I</i> site and footpad scale about three psi (20 kPa); surface material found to be small, cohesive particles with rocks up to three feet (1 m) in size; no loose dust. 10,300 pictures taken during first lunar day; 900 during second, last contact Jan. 7, 1967.
<i>Lunar Orbiter I</i>	Aug. 10, 1966	Moon	Lunar photography: Total of 207 frames of medium and high resolution pictures taken; 38 from initial orbit, 169 from low orbit. Areas covered: nine primary and seven potential <i>Apollo</i> landing sites (including <i>Surveyor I</i> site), 11 backside and two Earth-Moon pictures. Medium resolution pictures good, high resolution smeared. Readout completed Sept. 13, 1966; intentionally impacted Oct. 29, 1966, to avoid interference with second mission.
<i>Lunar Orbiter II</i>	Nov. 6, 1966	Moon	Lunar photography: Spacecraft completed taking 211 frames of 422 medium and high resolution pictures on Nov. 26, 1966. Spacecraft responded to over 2,870 commands and performed over 280 maneuvers. Readout completed Dec. 6, 1966. Impacted Oct. 11, 1967.

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
<i>Lunar Orbiter III</i>	Feb. 5, 1967	Moon	Lunar photography: 422 medium and high resolution pictures taken. Readout completed for six primary sites, parts of six other sites. Partial readout returned on 31 secondary sites. Impacted Oct. 9, 1967.
<i>Surveyor III</i>	April 17, 1967	Moon	Lunar exploration: Achieved soft landing on April 20, 1967. Closed loop radar failed during landing and spacecraft landed three times on inertial guidance before its verniers cut off. Surface sampler experiment discovered pebbles at 6 inches (15 cm) depth and 10 psi (70 kPa) bearing strength. The spacecraft returned 6,300 pictures. Site: Oceanus Procellarum, 3.33°S, 23.17°W.
<i>Lunar Orbiter IV</i>	May 4, 1967	Moon	Lunar photography: First photos returned May 11, 1967. Problems developed with camera thermal door. Readout completed May 27, 1967. High resolution lunar photos taken of over 99% of frontside. Impacted Oct. 6, 1967.
<i>Mariner V</i>	June 14, 1967	Venus	Planetary exploration: All science and engineering subsystems normal through encounter with Venus; data indicates Venus has a Moon-like effect on solar plasma and strong H ₂ corona comparable to Earth's, 72% to 87% CO ₂ atmosphere with balance probably N ₂ , O ₂ . Closest approach, 3,900 km on Oct. 19, 1967.
<i>Lunar Orbiter V</i>	Aug. 1, 1967	Moon	Lunar photography: Last launch in the series of missions to perform mapping of entire lunar surface. Provided detailed coverage of 36 scientific sites; five <i>Apollo</i> sites; completed high altitude far side coverage; a full view of Earth in near full phase. One hundred percent readout accomplished of all 212 frames taken; provided near-lunar micrometeoroid and radiation data. Impacted Jan. 31, 1968.
<i>Surveyor V</i>	Sept. 8, 1967	Moon	Lunar exploration: First alpha scatter data; indicated basaltic character of area sampled in Mare Tranquillitatus, 23.19°E and 1.52°N. Achieved 83 hours alpha scatter data and 18,006 photos in first lunar day. Survived first lunar night but, as expected, subsequent data obtained of lower quality.
<i>Surveyor VI</i>	Nov. 7, 1967	Moon	Lunar exploration: Sinus Medii, 0°25'N, 1°3'W Nov. 10, 1967. 30,100 TV pictures, 27 hours surface alpha scatter analytical time obtained. First liftoff from lunar surface: moved 10 feet (3 m) to a new location. Sixth in a series of seven <i>Surveyor</i> flights intended to perfect the technology of soft landing on the moon and provide basic scientific and engineering data in support of <i>Apollo</i> .
<i>Surveyor VII</i>	Jan. 7, 1968	Moon	Lunar exploration: Last <i>Surveyor</i> ; emphasized scientific objectives, landed on Tycho ejecta blanket, 40.89°S, 11.44°W Jan. 10, 1968; first combination of the three major experiments: TV (2,300 on first day), alpha scatter (43 hours surface analytical time), and surface sampler.

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
<i>Apollo VIII</i>	Dec. 21, 1968	Moon	First manned <i>Saturn V</i> flight: Frank Borman, James A. Lovell, Jr., and William A. Anders, demonstrated crew, space vehicle, and mission support facilities performance during 10 orbits around the Moon. Mission lasted 147 hours and returned to Earth Dec. 27, 1968.
<i>Mariner VI</i>	Feb. 25, 1969	Mars	Planetary exploration: Mid-course correction successfully executed to achieve a Mars flyby within 3,330 km on July 31, 1969. Designed to perform investigations of atmospheric structures and compositions and to return TV photos of surface topography. Returned 75 images of Mars.
<i>Mariner VII</i>	Mar. 27, 1969	Mars	Planetary exploration: Spacecraft identical to <i>Mariner VI</i> Mid-course correction successful for 3,518 km flyby on Aug. 5, 1969. Returned 126 images of Mars.
<i>Apollo X</i>	May 18, 1969	Moon	Manned lunar mission development flight to evaluate Lunar Module (LM) performance in the cislunar and lunar environment. Eugene A. Cernan, John W. Young, and Thomas P. Stafford. Major activities: descent of LM to within 50,000 feet (15,000 m) of lunar surface and 19 color television transmissions. Pacific splash-down May 26, 1969. 192 hours duration.
<i>Apollo XI</i>	July 16, 1969	Moon	First manned lunar landing: conducted limited selenological inspection, photography survey, evaluation, and sampling of the lunar soil. Assessed the capability and limitations of astronauts and their equipment in the lunar environment. Astronauts: Neil A. Armstrong, Michael Collins, and Edwin E. Aldrin, Jr. Touchdown on lunar surface July 20. Pacific splashdown July 24, after a flight of 195 hours duration.
<i>Apollo XII</i>	Nov. 14, 1969	Moon	Second manned lunar landing mission: demonstrated point landing capability, sampled more area, deployed Apollo Lunar Surface Experiment Package (ALSEP), investigated the <i>Surveyor III</i> spacecraft, and obtained photographs of candidate exploration sites. Astronauts: Charles Conrad, Jr., Richard F. Gordon, Jr., and Alan Bean. Touchdown on lunar surface was November 19. Total lunar EVA time was 15 hours 30 minutes. Total flight time was 10 days, 4 hours 36 minutes. Splashdown Nov. 24, 1969.
<i>Apollo XIV</i>	Jan. 31, 1971	Moon	Third manned lunar landing. Astronauts: Alan B. Shepard, Stuart A. Roosa, and Edgar D. Mitchell. Total flight time 216 hours. Splashdown occurred in Pacific Ocean on Feb. 9, 1971.
<i>Mariner IX</i>	May 30, 1971	Mars	Entered Mars orbit on Nov. 13, 1971. Spacecraft responded to 38,000 commands and transmitted 6,900 pictures of the Martian surface. All scientific instruments operated successfully. Mission terminated on Oct. 27, 1972.

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
<i>Apollo XV</i>	July 26, 1971	Moon	Fourth manned lunar landing and first of <i>Apollo "J"</i> series missions which carried the Lunar Roving Vehicle. Astronauts: David R. Scott, Alfred M. Worden, and James B. Irwin. Total flight time: 295 hours. Total lunar EVA time: 18 hours, 34 minutes. Worden conducted a 38-minute, in-flight EVA out of Earth orbit. Splashdown in Pacific about 300 nautical miles (600 km) due north of Pearl Harbor on Aug. 7, 1971. Approximately 180 pounds (82 kg) of rock and soil samples returned.
<i>Pioneer 10</i>	Mar. 3, 1972	Jupiter	Investigation of the interplanetary medium, the asteroid belt, and the exploration of Jupiter and its environment. Closest approach to Jupiter 130,000 km on Dec. 3, 1973. Exited Solar System June 14, 1983; still active.
<i>Apollo XVI</i>	Apr. 16, 1972	Moon	Fifth manned lunar landing; second of the <i>Apollo "J"</i> series with the Lunar Roving Vehicle. Astronauts: John W. Young, Thomas K. Mattingly II, and Charles M. Duke. Total flight time was 266 hours. Total lunar EVA time 20 hours 14 minutes. Mattingly's in-flight EVA was 1 hour 23 minutes. Splashdown in Pacific Ocean. April 27, 1972. Approximately 213 pounds (97 kg) of samples returned for scientific study.
<i>Apollo XVII</i>	Dec. 7, 1972	Moon	Sixth and last manned lunar landing; third of the <i>Apollo "J"</i> series which carried the Lunar Rover. Flight crew Eugene A. Cernan, Ronald E. Evans, Harrison H. Schmitt spent 302 hours in flight. Cernan and Schmitt completed three lunar EVAs lasting a total of 22 hours. The U.S.S. <i>Ticonderoga</i> recovered the crew and approximately 250 pounds (113 kg) of samples on Dec. 19, 1972.
<i>Pioneer 11</i>	Apr. 6, 1973	Jupiter/ Saturn	Obtained scientific information beyond the orbit of Mars with the following emphasis; (a) investigation of the interplanetary medium; (b) investigation of the nature of the asteroid belt; (c) exploration of Jupiter and its environment. Closest approach to Jupiter 34,000 km on Apr. 19, 1974. Encountered Saturn on September 1, 1979.
<i>Mariner 10</i>	Nov. 3, 1973	Venus/ Mercury	Conducted exploratory investigations of the planet Mercury during three flybys by obtaining measurements of its environment, atmosphere, surface, and body characteristics, and conducted similar investigations of Venus. Encountered Venus on Feb. 5, 1974 and Mercury on Mar. 29 and Sept. 21, 1974, and Mar. 16, 1975. Resolution of the photographs was 100 m, 7,000 times greater than that achieved by Earth-based telescopes.
<i>Viking 1 Lander and Orbiter</i>	Aug. 20, 1973	Mars	Scientific investigation of Mars. United States' first attempt to soft land a spacecraft on another planet. Successfully soft landed on July 20, 1976. First <i>in situ</i> analysis of surface material on another planet.

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
<i>Viking 2 Lander and Orbiter</i>	Sept. 9, 1975	Mars	Scientific investigation of Mars. United States' second attempt to soft land on Mars. Successfully soft landed on Sept. 3, 1976 and returned scientific data. Orbiter from both missions returned over 40,000 high resolution photographs showing surface details as small as 10 meters in diameter. The Orbiter also collected gravity field data, monitored atmospheric water levels, thermally mapped selected surface sites.
<i>Voyager II Voyager I</i>	Aug. 20, 1977 Sept. 5, 1977	Jupiter Saturn Uranus Neptune	<i>Voyager II</i> encountered Jupiter July 9, 1979, Saturn Aug. 26, 1981, Uranus January 24, 1986, and Neptune August 25, 1989. <i>Voyager I</i> encountered Jupiter Mar. 5, 1979, and Saturn Nov. 13, 1980. Both returned a wealth of information about the giant planets and their satellites including documentation of active volcanism on Io, one of the Galilean satellites; still active. <i>Voyager II</i> at Neptune discovered geysers on Triton.
<i>Pioneer 12 Pioneer 13</i>	May 20, 1978 Aug. 8, 1978	Venus Venus	Orbiter, launched in May, studied interaction of the atmosphere and the solar wind and made radar and gravity maps of the planet. The multi-probe spacecraft, launched in August, returned information on Venus' wind and circulation patterns as well as atmospheric composition, temperature and pressure readings. Pioneer 12 entered Venus orbit Dec. 4, 1978 and Pioneer 13 encountered Venus Dec. 9, 1978.
<i>Magellan</i>	May 4, 1989	Venus	Planetary Exploration: Designed to study geological structure of Venus including its density distribution and dynamics. Synthetic aperture radar provided detailed topographic maps over 98% of surface with resolution of 100 m and maps of the Venus gravity field. Magellan deliberately commanded into Venusian atmosphere where it finally burned up on Oct. 12, 1994.
<i>Galileo</i>	Oct. 18, 1989	Jupiter	Planetary exploration: Designed to perform in-depth studies of Jupiter's atmosphere, satellites, and surrounding magnetosphere. Deployed probe into Jovian atmosphere on Dec. 7, 1995. Orbiter portion of mission still active with numerous encounters with satellites planned.
<i>Ulysses</i>	Oct. 6, 1990	Solar corona solar wind, Jupiter	Ulysses is a joint NASA/ESA mission designed to study the polar regions of the Sun, properties of the solar wind, interstellar and interplanetary gas. Spacecraft trajectory intercepted Jupiter and used its gravity to leave the ecliptic plane. Primary mission ended in October 1995 after first pass above northern pole of Sun. Presently in extended-mission phase.
<i>Mars Observer</i>	Sept. 25, 1992	Mars	Planetary exploration: Designed to study the surface, atmosphere, interior, and magnetic field of Mars for Martian orbit. Communications with spacecraft lost on August 22, 1993, before going into orbit.

Payload Name	Launch Date (GMT)	Mission	Mission Remarks
<i>Clementine</i>	Jan. 25, 1994	Lunar orbiter asteroid flyby	Clementine was jointly sponsored by Ballistic Missile Defense Organization (BMDO) and NASA. Primary objective was to space qualify various technologies. Clementine entered lunar orbit and provided 1.6 million images of Lunar surface. Spacecraft left lunar orbit for a planned encounter with asteroid Geographos but failed to rendezvous due to spacecraft anomaly.
NEAR	Feb. 17, 1996	Asteroid Eros	Near Earth Asteroid Rendezvous is the first launch in the NASA Discovery Program for small planetary missions. Primary scientific goals are to measure composition and structure of asteroid Eros.
<i>Mars Global Surveyor</i>	Nov. 7, 1996	Mars	Planetary exploration: MGS is the first mission of the Mars Surveyor Program. Designed as a polar orbiter; entered Mars orbit September 1997; global mapping is scheduled to begin late January 1998.
<i>Mars Pathfinder</i>	Dec. 4, 1996	Mars	Second launch in the NASA Discovery Program. The mission consists of a stationary lander and a surface rover. Touchdown occurred July 4, 1997. Returned over 9,000 images, plus soil analyses and weather data. Mission in extended phase.

CURRENTLY PLANNED SOLAR SYSTEM MISSIONS

- Beginning in November 1996, launches commenced for a series of small orbiters and landers to Mars. The first of these, the Pathfinder, successfully completed its primary mission in August 1997.
- The Cassini mission to Saturn will orbit the ringed planet and drop a European Space Agency probe into the atmosphere of its mysterious moon, Titan.
- The Near-Earth Asteroid Rendezvous (NEAR) mission will orbit an asteroid for the first time as part of the Discovery series of low-cost, high-technology spacecraft.
- The New Millennium program will develop advanced automation techniques and new microtechnology for future space missions. A succession of small, high-technology spacecraft will test these new technologies and return a continuous flow of information to Earth about the Solar System, and possibly even the existence of planets around nearby stars.
- The Lunar Prospector will map the composition and magnetic field of the entire Moon for the first time.
- The Stratospheric Observatory for Infrared Astronomy (SOFIA), an airborne telescope, will study star and planet formation as well as the dynamics and chemistry of the interstellar medium.
- The STARDUST spacecraft will fly through a cometary coma, collect dust from the coma, and return it to Earth.
- The Space Infrared Telescope Facility (SIRTF), the fourth and final Great Observatory, will study debris disks around stars to understand the frequency of occurrence and properties of the disks as an aid to understanding the frequency of occurrence of planets and to physical conditions in the primitive solar nebula.

APPENDIX C

ACRONYMS

ACRONYMS

ALSEP	Apollo Lunar Surface Experiment Package
COMPLEX	Committee on Lunar and Planetary Exploration
D/H	deuterium to hydrogen (ratio)
DSN	Deep Space Network
EVA	extravehicular activity
IR	infrared
Isp	specific impulse
Lidar	Light detection and ranging
NEAR	Near-Earth Asteroid Rendezvous (mission)
OPS	operations
OSS	(NASA) Office of Space Science
S/C	spacecraft
SEP	solar electric propulsion
SIRTF	Space Infrared Telescope Facility
SNC	shergottite, nakhlite, and chassigny (meteorites; group of similar meteorites thought to originate from Mars)
SOFIA	Stratospheric Observatory for Infrared Astronomy

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